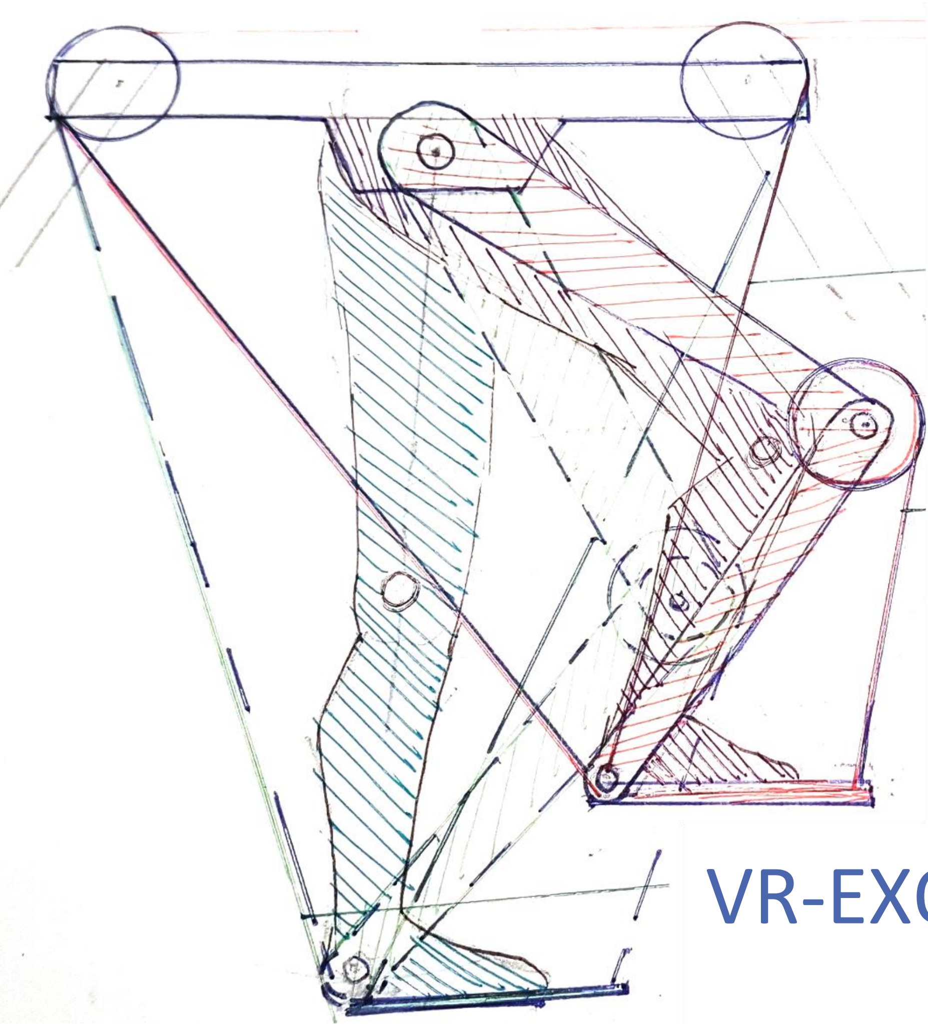

VR-EXO - RESEARCH

17/12/2018

Abstract

Real world space limitations and motion sickness persist to be large problems in Virtual Reality (VR). To solve these problems, multiple companies have tried making omnidirectional treadmills and slide-mills. Omnidirectional treadmills still have inertia problems in switching directions and slide-mills have problems with friction feeling like “playing laser tag on ice, wearing bowling shoes”. All these options are made for a flat surface only.

The AxonVR suit is made to also be able to step onto heights, such as stairs. However, their solution currently only provides slow movement. Other possibilities of constructions are considered to make sure there is no cheaper and easier option. In these options it is important that they would not only make you able to run and step on surfaces, but that also will fit a wide variety of person lengths. In the future, the goal is to expand VR-exo may to even rotate the user in multiple degrees of freedom. This creates not only a running simulator, but at the same time a race, flight and everything-you-can-think-of simulator.

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1 THE VISION OF VR-EXO

Virtual reality (VR) is a great concept, which allows users to visit a virtual world using a headset. Currently, there are large open worlds, but usually only a small space to play in someone's living room. This confines free movement of the user to the space of his living room. A current option is to use 'teleportation' or 'free locomotion' in games. With teleportation the user points at a spot in the virtual world and appears there. With free locomotion, the user can control his movement with a touchpad or joystick on the controller. This however induces motion sickness in many users, because movement in the virtual world, mismatches the movement felt by the body [1]. Thereby, the immersion is not optimal, for the user is not truly moving his legs to walk. The goal of VR-exo is to simulate the force feedback on the legs of the user to increase immersion and reduce motion sickness.
The idea of VR-exo started by thinking about the far future. How would the best VR experience look like? It would be an environment where you can feel force, climb any mountain and fly freely assisted all by one construction. Walk around and step in a car or plane and start racing or flying while feeling the forces. Feel the pressure of the objects you touch like in the normal world. Feel every force from every direction.

In the movie Ready Player One, this world is described. Like many sci-fi movies did, they can give inspiration for inventions that can be developed in the future [2]. In one of the movies first scenes, an omnidirectional treadmill is used for locomotion. In our world, slower versions currently exist, which will be covered in Chapter 2.2. In the final scenes, they seem to be using haptics using steel cables as well. This option would be much smaller to store than an omnidirectional treadmill.

Figure 1: ***The long-term goal, the option presented by AxonVR/HaptX [44]***

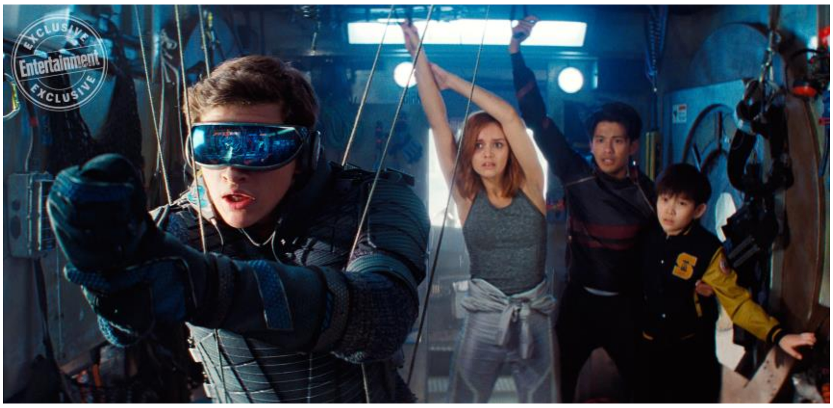

Figure 2: ***The more compact solution in the sci-fi movie Ready Player One. (video) According to one of the first scenes in the movie, they use a omnidirectional treadmill for running, but this might not be needed if they are hanging in steel cable haptics as seen in the scenes at the end of the movie.***

VR-exo will not only focus on entertainment purposes. There are many possibilities in therapeutic applications, to train people to walk again. The more realistic this motion is, the better it will help for a correct simulation of movement and faster training. This also applies to field training, such as for the military, fire-fighters or other active trainings.

None of the solutions below can do that. You are limited to a 2D floor, you can only sit in some options, but you can in no way control forces on the legs of the user.

1.1 THE GOAL

The optimal and very long-term goal will be a construction wherein the user can be spun around in all degrees of freedom possible in addition to having haptic feedback forces applied to every action thinkable. In the final product, the user should be able to walk, tilt and sit in every position possible, while always having the correct forces countering the actions of the user. Of course, in the short term this is not possible, but working towards it is possible.

Therefore, VR-exo should be a kind of exoskeleton, which allows to control movement of the legs in VR. When a user places his foot in front and would touch the floor in VR, the construction will pull back on the foot to keep it in place. Then, when the user moves his foot backwards in the step, the surface will move backwards with the foot in a straight line. For the first prototype, there will be focus on moving forwards in a straight line only, without sidestepping, to keep te project less complex and extend its capabilities step by step.

The design in Figure 3 relies on steel cables rolling in and out with motors. In time, this may be like the steel cable solution in Ready Player One, visible in Figure 2. This can be developed to be much more compact to store than most other options, which requires a large installation in the living room. There are some drawbacks that come with each of the current designs, which will be discussed in Chapter 7.

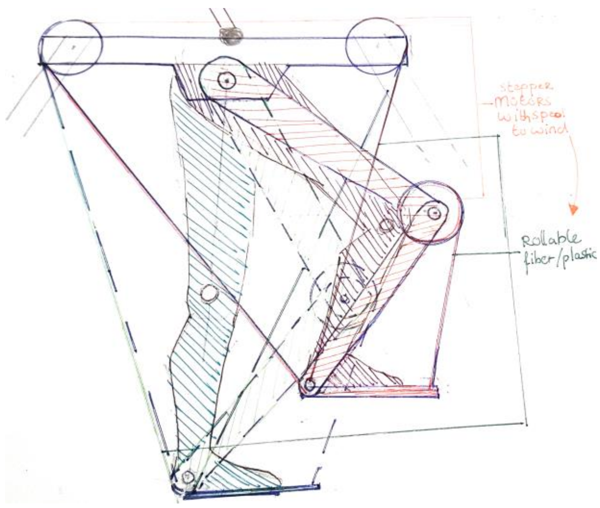

Figure 3: The very first design of VR-exo.

2 CURRENT AVAILABLE HAPTICS AND MOTION DEVICES FOR VR

Currently, there are a few options on the market that address this problem as well. Below, each product will be evaluated for the advantages and disadvantages that have been found. Then the vision of VR-exo and a few designs that have been made will be discussed. In addition to hardware, the current solutions rely mostly on software related solutions.

2.1 SOFTWARE SOLUTIONS

There are many software solutions of which most are explained in this video. In most games, the user can choose between teleporting or locomotion. In teleporting, the user points at a spot on the ground with a controller and clicks a button to appear there, see Figure 4. Locomotion provides smooth movement, by moving a joystick on the controller or with a touchpad. This method would be preferred, if it would not cause motion sickness in 25 – 40% of the users [1]. This is considered to be large enough of a problem to search for alternatives. Other options are swinging arms, pulling on an invisible rope or head bobbing up and down to move forward.

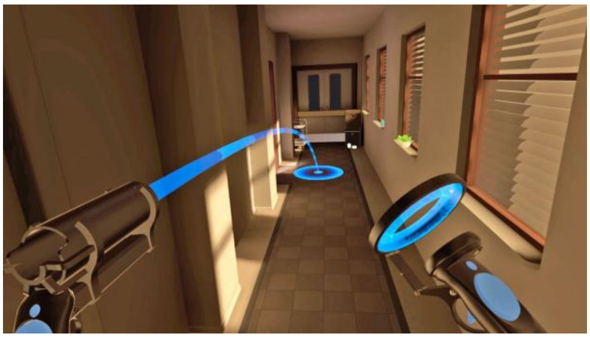

Figure 4: Teleport 'walking' in VR. The user points at a location. When a button on the controller is pressed, the user appears at that point.

Recently, scientists from Stony Brook University, NVIDIA and Adobe have collaborated on a computational framework to provide infinite walking in a room scale space, see Figure 5. During the time the user takes to focus his eye at a different object, the user does not take any visual input. Using eye-tracking, this moment can be registered, and the virtual world can be shifted slightly. This way, the world can be shifted while the user does not notice this. If the world is shifted, the user is prompted to walk in a different direction, without him even knowing it. The movement of the eye can be also induced by creating a flashing spot in the vision of the user. The user will focus on the flashing dot. In this moment the world can be slightly rotated as well. [3]

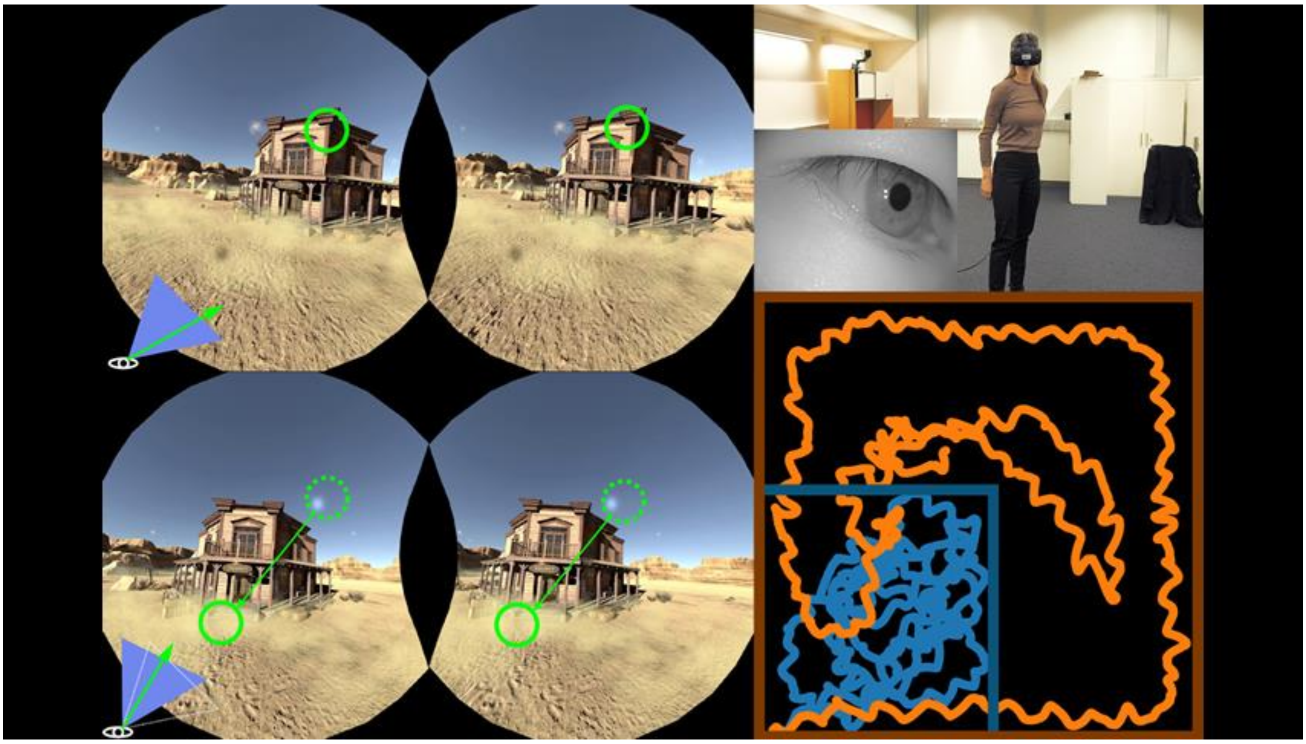

Figure 5: Infinite walking in VR. While rotating the virtual world when the user walks close to the egde of a room, the user is influenced to walk in a different direction in real space, while traversing in the same direction in virtual space. By creating a shimmering light when the user is close to a wall, the user is distracted, and the world can be turned at will. This can be done very subtle to the point where the user does not notice the effect. [3]

2.2 OMNIDIRECTIONAL TREADMILLS

An omnidirectional treadmill is a treadmill which allows movement in 360° on a flat surface. There are currently multiple designs on the market, with the most prominent being Omnideck by Omnifity and Infinadeck.

Figure 6: T*he omnideck during a demonstration* [40] *(video 1, video 2)*

Figure 7: *The Infinadeck during a demonstration* [42]. *(video)*

2.2.1 OVERALL DISADVANTAGES

All omnidirectional treadmills have a few disadvantages in common:

- They are large and expensive.

- When a user stops moving, or starts moving in an opposite direction, the built-up momentum must be cancelled out. This causes the user to feel like he is in fact moving backwards, causing instability. It is described in this video.
- There is no adjustment for increasing the floor height when a user meets an incline and the user cannot for instance walk stairs.

Below only advantages and disadvantages relative to other designs will be discussed.

2.2.2 OMNIDECK

Figure 6 shows the Omnideck, which consists of planes of rollers, oriented in a circle. The headset position is measured, and when the user steps out of the center the rollers will gently spin to bring the user back to the origin. This can be done while the user is still continuously walking to create the effect of a treadmill.

ADVANTAGES WITH RESPECT TO INFINADECK

- As visible in demo's, the user can walk without support or falling by trained people. No demonstrations have been found for first-time users.
- The user can crawl, visible in this demonstration.

DISADVANTAGES WITH RESPECT TO INFINADECK

- The Omnideck by Omnifinity can be considered very large, with a diameter of 4.2m [4].
- The rollers spin relatively slow in every demonstration. No mention of being able to run on it has been found.

2.2.3 INFINADECK

Figure 7 shows the Infinadeck. Infinadeck is a treadmill, where the treadmill consists of tiny treadmill bands in the perpendicular direction. It looks like there are many separate small bands, but actually it is one large spiraling band [5]. A tracker is attached to the waist of the user near the centroid. The treadmill keeps the user in the center by moving the treadmill when the centroid moves out of the center.

ADVANTAGES WITH RESPECT TO OMNIDECK

- When trained to walk stable on the Infinadeck, the CEO claims running is possible up to 8 miles an hour (= c.a. 13 km/h), although no demonstration is given. [6]
- Power consumption under 1200 watts.
- It is compact with respect to the Omnideck, without the stabilization ring on top. (1.72 L x 1.63 W x 0.425 H) and a weight of 255kg. [7]

DISADVANTAGES WITH RESPECT TO INFINADECK

- It is not much more collapsible than the current form for storage or transport.
- It makes some noise ~70dB [7].
- When a user bends over or crouches, the centroid of the user will move, which causes the floor to move. This gives an instable feeling doing this.

2.3 SLIDE-MILLS (SOMETIMES ALSO CALLED OMNIDIRECTIONAL TREADMILLS)

Slip rings are a kind of omnidirectional treadmills, but instead of moving on a moving treadmill, the user walks on a fixed surface with little friction. The user is usually held by a construction attached to the waste, to keep him in place. When the user steps, his foot will slip back to the bottom of the semicircle. Many companies have built something like this, but the most prominent are KAT-WALK by KAT-VR, Virtuix Omni by Unbound VR and Virtualizer by Cyberith.

Figure 8: *Virtuix Omni* [43]

Figure 9: *KAT-Walk* [15]

Figure 10: Virtualizer by Cyberith

ADVANTAGES

The slip mills have a few advantages compared to omnidirectional treadmills:

- They are smaller (Virtualizer: 130cm x 130cm x 107cm, 40 kg). [8]
- They contain fewer moving parts, making them less susceptible to breaking.
- Moving speed has no restrictions by the hardware.

DISADVANTAGES

- The most major disadvantage is that due to the curved shape and the constant low friction on the shoes, movement does not feel natural. Users have often described it as feeling like ice-skating [9] or “playing laser tag on ice, wearing bowling shoes” [10] and “Walking on a ‘slippery plastic saucer’ is about as natural as it sounds” and “confined in a dish and pushing awkwardly against it”. Some people even say walking in place to move forwards or locomotion with software only is more immersive [11].
- The user is being hold at the waist, which can make the experience feel limited. Except for in the Virtualizer, you cannot crouch or pick objects up from the ground.
- Users cannot take other positions than running. In Kat-VR sitting is also possible. Stepping onto objects in VR is not possible.

2.3.1 VIRTUIX OMNI

Virtuix omni was the first slip-mil to be launched on Kickstarter (Jun 4 2013 - Jul 23 2013 (48 days)). It was funded for $1,109,351 pledged of a $150,000 goal (which is 740%) by 3,249 backers. This was an amazing leap for VR locomotion, however, there are some downsides to this design. The waist height is fixed, which means only very limited sizes of people can fit in, leading to frustrations [12]. Since the waist cannot move up and down, this also means you cannot jump. The walking motion does not feel natural and has been described as: “playing laser tag on ice, wearing bowling shoes” [10].

Additionally, shipping costs due to the size (123cm x 110cm, 80 kg), have been a major problem in getting the product to the Kickstarter backers. They have been offered a regulation to get their money back or pay $250 to $600 shipping-costs to receive their Virtuix Omni. They also stated that “The hardest part of fulfillment is not the initial delivery of the Omni and various accessories (albeit costly and complicated) but complying with international regulations and the global shipping and storing of replacement parts necessary to effectively support a range of geographically diverse customers.” [13]

2.3.2 KAT-WALK

KAT-WALK has raised $149,278 by 231 backers to complete its goal with 150%. KAT-WALK is more promising than the Virtuix Omni especially due to the holding bar being behind the back, allowing free arm movement. However, the walking still does not feel completely natural. The reason why they are not around everywhere yet, is once again the shipping costs. [14] The dimensions are still larger than those of the Virtuix Omni with 150cm×150cm×200cm and 85kg. [15]

2.3.3 VIRTUALIZER

The Virtualizer is a great Kickstarter result on first glance. They had 577 backers which pledged $361,452 which made them achieve their goal with 145%. It is still bulky with 130 cm x 130 cm x 107 cm and 40 kg. [8] However, it becomes evident that they have never shipped a single Virtualizer to their Kickstarter supporters and are not planning to. This makes most people steer clear from them, although they do seem to build units locally at a business price of over $6000. [16] Large advantages in comparison to the Virtuix Omni and KAT-WALK is that you can crouch in the Virtualizer.

2.4 EXOSKELETONS IN DEVELOPMENT

2.4.1 SELF-WALKING AND ASSISTING EXOSKELETONS

There are many exoskeletons that can help paraplegic people walk or support workers. Examples of exoskeletons that can walk by themselves, are built by the University of Twente (video) and TU Delft (video). The differences with an exoskeleton for the goal of VR-exo, is that in VR-exo the user should be able to walk by himself and the exoskeleton should only push back when the users foot encounters a floor in VR. The user should have as much freedom as possible when lifting a foot forward. If the user must push through multiple motors, the walking does not feel natural since it is too heavy. I have talked with them and I know most technical details of their project. However, it is out of the scope of this paper to list it all here.

2.4.2 AXONVR SUIT BY HAPTX

One exoskeleton that is very similar to VR-exo is the AxonVR exosuit (video) by HaptX, see Figure 11. It has the same vision as VR-exo. The video about their development on the exoskeleton originates from 2016. In the video is shown that the user can walk stairs very slowly. Of course, this exoskeleton was still under development. They currently seem to have halted the development of the full suit and first seem to focus on making touch feel genuine. They have landed a patent in 2017 for a full body suit simulating life-like touch [17]. Currently, they have near finished prototypes of Glens, also called HaptX glove, which uses that patented technique of simulating touch.

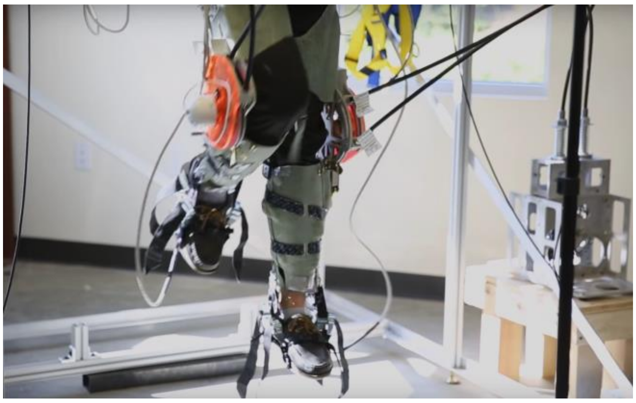

Figure 11: The AxonVR suit. (video)

Since the product is not out on the market yet, and HaptX remains secretive, it is hard to figure out their current design problems. From what can be seen in the video, the movement is very slow and does not look perfectly coordinated. This is probably partially connected to the software but could also be due to other problems. Thereby, the AxonVR suit seems to be made one size only. It does not seem easily adjustable for other leg lengths.

2.4.3 HAPTX GLOVE

There are many haptic gloves on the market, but none has as much functionality as the HaptX glove (video). With these gloves you can feel shape, texture, motion [18] and temperature [19] of virtual objects. It uses 130 inflatable points that can displace your skin up to 2mm with microfluids. Thereby, it provides force feedback by pulling on the back of the fingers when the user picks up an object. This makes feeling hardness or squishiness also possible. [18] The HaptX glove is still very bulky and their next step is to bring the size down. [20]

Figure 12: Glens, the HaptX Glove [20]. (video)

2.4.4 DEXTRES

DextrES (Figure 13) is a very slim and light glove that can provide haptic feedback. It was developed by scientists from the Advanced Interactive Technologies Lab at ETH Zurich and EPFL. It can fix the user's fingers in place and can provide feedback using small vibrations on the fingertips. Each finger has two sliding stainless-steel plates attached. By placing opposite electrostatic charges on the two plates, they can attract each other, creating up to 40N of force [21], holding the finger in place. [22]

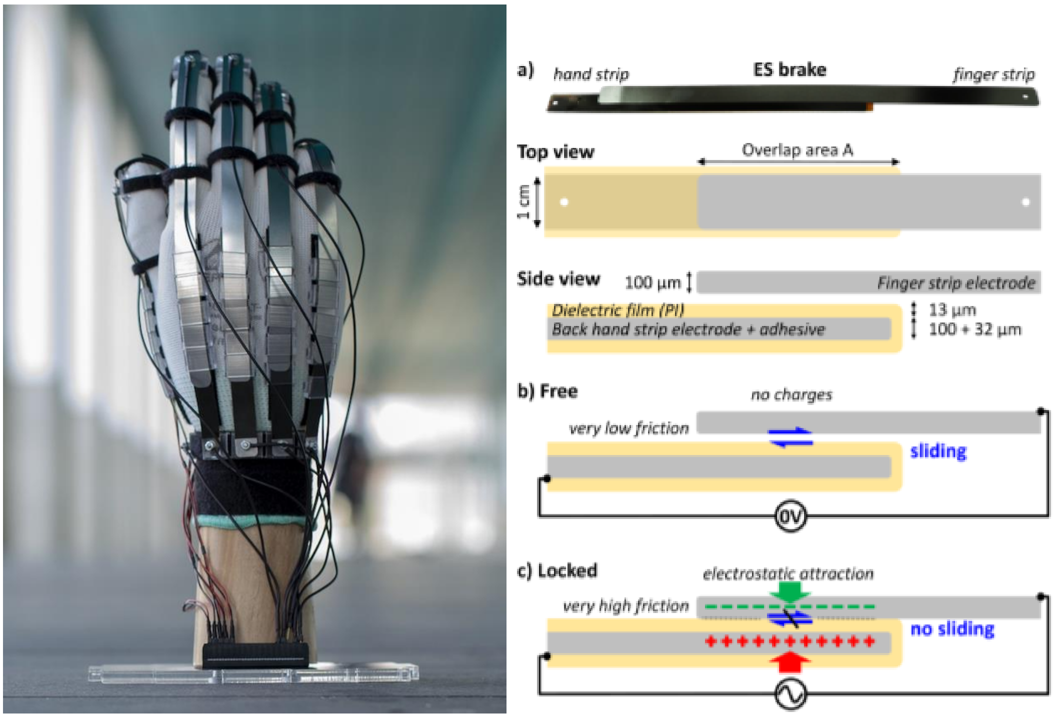

Figure 13: DextrES, a very light glove (< 8 grams/finger [21]) that can hold the finger in a certain position. It consists of two parallel plates that can slide freely over each other. By applying opposite electric fields on both plates, they attract each other. This provides an electrostatic attraction between them, creating a clutch up to 20N. [22] Left image from [45]. (Video)

2.5 TESLASUIT

Previous developments were all based on keeping the user from grasping through objects and creating realistic force feedback on grabbing or walking. The Teslasuit is not used for this kind of feedback, but for the sensation of touch and getting hit. Unlike the HaptX glove which uses inflatable 'pixels' [19], the Teslasuit creates the sensations by electrical stimulation [23].

Figure 14 shows the Teslasuit. It contains haptic feedback with electrical stimulation, motion capture, climate control and a biometric system. The user can feel for instance when they get hit by a bullet and the suit can cause muscles to contract. Currently, only the green patches contain electric stimulation [46]. Due to muscle contraction, the user can also feel recoil of shooting a gun [47]. Image [23]. (video)

2.6 CYBERSHOES

The most heard arguments against omnidirectional treadmills are that they are expensive and too large to fit in someone's living room. Cybershoes are the solution for many players with low budgets and small spaces. The Cybershoes can be strapped on the user's shoes. By sitting on a rotatable stool, you can move your feet across a carpet to walk in VR. The movement across the carpet is registered by the roller underneath the Cybershoe. Their Kickstarter was launched at 2nd of October 2018 until the 1st of November 2018. On the first day they were funded 333% for an amount of $115,000 [24]. At the end of the Kickstarter, the final raised sum was $243,884, raised by more than 1000 backers.

Figure 15: Cybershoes are small and relatively cheap and provide locomotion in VR. The user sits on a rotatable stool and can make a walking motion across a carpet to rotate the rollers beneath the shoes. This motion is then converted to movement in VR.

3 ENGINEERING DECISIONS

3.1 FOCUS

All above stated technologies have their advantages and disadvantages. The most heard disadvantages of an omnidirectional treadmills, most people say they are expensive, large and heavy. Thereby, walking on them does not feel completely stable, especially when changing directions. For slide-mills, this is mostly the same, but the walking feels even less natural. With these solutions, it will also be hard to apply haptic feedback to different situations. Tilting to simulate walking up a hill is possible, but for instance stopping a foot because it bumps into a table leg, is not naturally possible with these solutions. VR-exo wants to focus on stopping the foot in these cases as well.

Since the Teslasuit and HaptX are already focusing on touch feedback in VR across the entire body, VR-exo will focus on the force feedback only.

The other requirements will be discussed in Chapter 0.

3.2 TRACKING

Currently, there are many good tracking systems on the market. The easiest way to incorporate tracking into your own projects is with an HTC Vive tracker. The controllers are tracked with the same technology as the external trackers you can buy. With an API, the trackers can be used in software as Unity to make an application with the tracked positions. This can be used to track the feet. Since this is a relatively easy way to track the feet, this will be used initially in developing VR-exo and will not be a major focus of the project.

3.3 BIOMECHANICS

To create a movement of the exoskeleton that feels as natural as possible, an extensive study should be done at several movement gaits. Examples are standing stil to walking, walking to standing still, running and in later versions turning around. There should be looked at the changes in forces so an accurate prediction of what the user will attempt to do can be as accurate as possible. Only then, the foot will be stopped at the right times at the right position and will move back in a correct line with the users foot.

The requirement is that the construction will support users at least up to 100kg to fit a range of users. The force that is exerted by gravity is given by F = m*a, with F the force in Newton, m the mass in kg and a the acceleration in m/s^2 (c.a. ~10 m/s^2 for gravity). This means that when the user stands still, about 1000N will hang on the construction. When the user runs, the forces increase due to an additional acceleration of the weight.

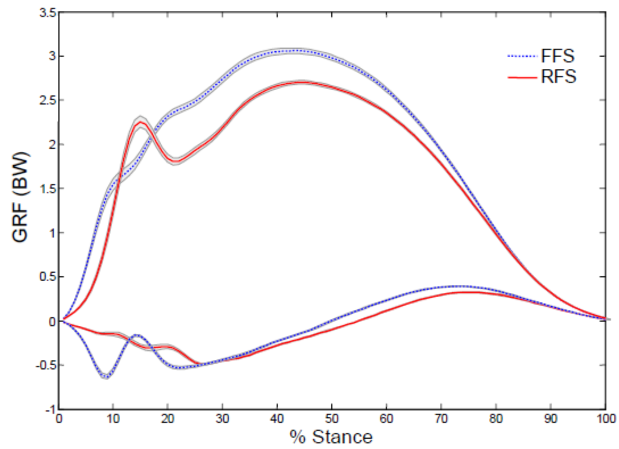

Figure 16: The forces on the ground during running in the percentage of body weight. It is shown for both the fore foot stride (FFS) as the rear foot stride (RFS). The running speed at the measurement was 4.25 (0.26) m/s for RFS and 4.37 (0.23) m/s FFS. It shows both the vertical and anterior-posterior (AP) GRF (ground reaction force) [25] From this can be concluded that at around 4.37 m/s (=15.7 km/h) the force will be around 3.2 times the body weight in the vertical direction and 0.7 times the body weight in the horizontal direction. [25]

3.3.1 FORCES IN MOVEMENT

Some people run with a forefoot strike pattern (FFS) and others with a rearfoot strike pattern (RFS). The forces on the ground can be determined by measuring the ground reaction force (GRF) when the foot hits a force detector in the floor. This can be measured in the vertical direction (vGRF) and in the anterior–posterior direction (hGRF). There is an impact (or breaking) peak when the foot hits the floor and an active (or propulsive) peak when the user propels himself forwards. This is especially visible with the RFS pattern, see Figure 16. This figure shows that at 4.37 m/s (= 15.7 km/h), the vGRF is around 3.2 times the body weight (BW) [25]. For 5 m/s (= 18 km/h) which will be the maximum speed for VR-exo, the maximum vGRF is 2.83 BW and the hGRF is 1.26 BW which was calculated from the body weight impulse and stance times. The stance time for 5 m/s is 199 ms [26]. The vGRF of that research is lower than the vGRF of the research at 4.37 m/s. Other researches give speeds around 2.7 BW as well [27] or even 2.5 BW for 6 m/s [28], but since one high measurement has been found, the 3.2 BW will be used to be sure.

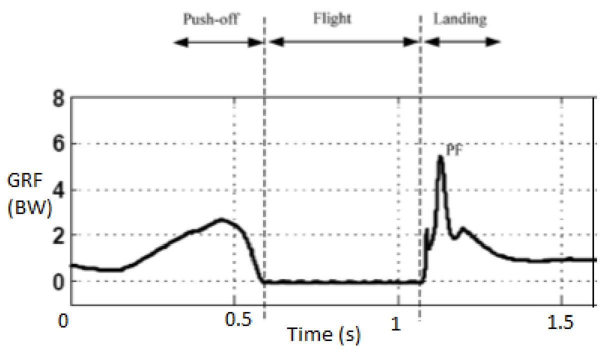

Figure 17: The ground reaction force during a maximal vertical jump. This can be up to 6 times the body weight during landing. [35]

The prior forces given are forces during a constant run. However, larger forces are visible with vertical jumping (see Figure 17). The forces during landing from a maximal jump can be up to 6 BW. This force will not be evaluated for this version of VR-exo.

3.3.2 MINIMUM AND MAXIMUM LENGTHS

Dutch men are the tallest in the world [29]. At P = 90% Dutch men are 195.1 cm. To make sure most people can fit the VR-exo, this population will be looked at for the maximum leg length that should fit. The hip height at P = 90% among Dutch adults from 20-30 is 108.6 cm [30]. This will be used as a final leg length that should fit the VR-exo. Children from 8 years should also be able to fit in the VR-exo. In Europe, they are about 120 cm long, and have a hip height of 68 cm [31]. This will be used as the approximal minimum size that should fit the VR-exo. To calculate the ratio between the lower and upper legs, the average lower leg length to thigh leg length will be used. For Americans, the following results have been found. The buttock-popliteal length (from the back while sitting, to the inner knee) is 59.2cm on average. Their knee-height (bottom foot to the top of the knee) is 54.1cm. [32] This gives a proportion of lower to upper leg of 0.91. This means that for the longest leg length, which is used to calculate, the upper leg is 59cm long and the lower leg is 49cm long. The foot length at P=90% for men in the Netherlands is 288mm. [30] 30 cm will be used as the length of the foot plateau.

3.3.3 JOINT ANGLES

The joint angles during a 3.89 m/s run are shown in Figure 18. These will be used to see what positions the skeleton should take within 200 ms (see Section 6.2 for 200 ms and Chapter 7 for where the angles are used in calculations).

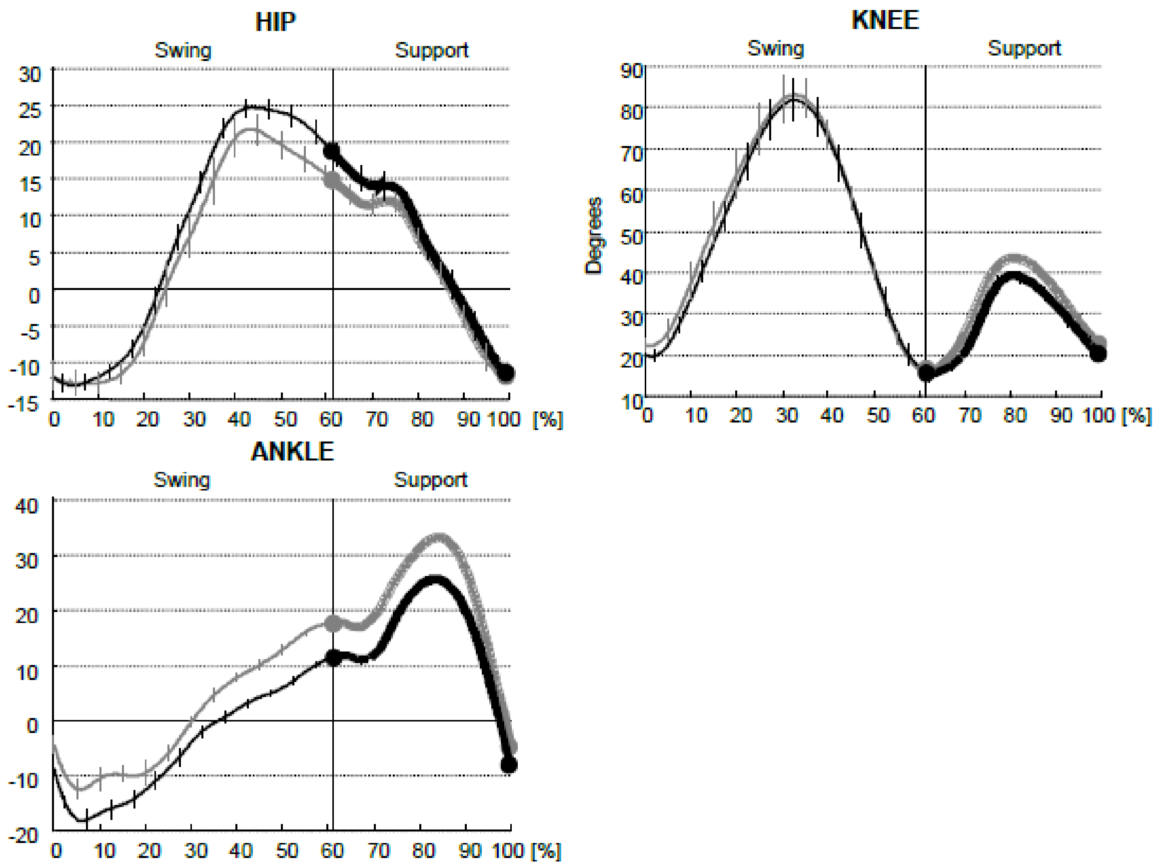

Figure 18: Lower limb joint rotation plots in the sagittal plane for one subject at 3.89 m/s. The light and dark grey are the left and right leg respectively. [37] The support start and end are also drawn in skeleton shape in Figure 28.

3.4 MECHANICAL LIMITS

3.4.1 STEPPER MOTORS

The possibilities in construction are limited by what motors and materials can provide us. Stepper motors have as advantages that [33]:

- They can drive a wide range of frictional and inertial loads.
- Need no position feedback to control the position.
- Are relatively inexpensive.
- Have an easy setup and use.
- They have a long lifetime.
- At low speeds, they have high torque and barely need gearing.
- Returns to the same location accurately.
- The motor cannot be damaged by mechanical overload.

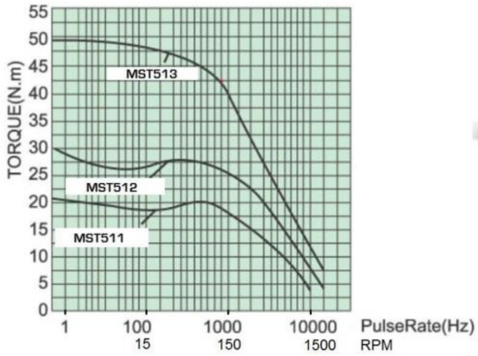

Figure 19: The torque and rpm of heavy-duty stepper motors by JVL. We will assume these torques are the limits of stepper motors, since I have not found higher torque vs RPM motors elsewhere. [51]

Heavy duty stepper motors have their limits. I have not been able to find more heavy-duty motors than JVL stepper motors. Figure 19 shows the torques vs RPM graph of their most heavy-duty motors, which can run on 220V. However, they mention: “Torque curves are measured at driver voltage 310VDC and half step operation. If lower driver voltage is used, torque will decrease accordingly for speed above 50-100RPM.” Therefore, the final output torque will probably be lower. With harmonic drives, the speed can be decreased to increase the torque output. The optimum of torque to use is around 42.5 Nm, after this the torque decreases exponentially with the speed.

Downsides of stepper motors are that [33]:

- The torque drops rapidly with speed
- They have a low accuracy
- They are prone to resonances.
- There is no feedback to indicate missed steps.
- Low torque to inertia ratio. Accelerating large loads rapidly is a problem.
- Motor gets hot in high performance scenarios, since it always draws substantial power, regardless of load.
- Motor will not resume rotation after momentary overload.
- Motor is audibly very noisy at moderate to high speeds.
- Low output power for size and weight.

Many of those disadvantages make clear that stepper motors are not the motors that should be used in this case. Especially since the torque to inertia ratio must be high for this application.

3.4.2 BRUSHLESS DC SERVO MOTORS

Brushless DC motors are a good alternative for stepper motors. The difference with regular brushed DC motors is that they of course have no brush. This brush is normally used to power the correct coil at the right time by brushing against them while rotating. This makes the timing of powering the coils easy, but there are many advantages of a brushless motor [33]:

- They have high output relative to motor size and weight.
- The encoder determines accuracy and resolution.
- They have high efficiency. It can approach 90% at light loads.
- High torque to inertia ratio. It can rapidly accelerate loads.
- Has reserve power and torque: 2-3 times power and 5-10 times rated torque for short periods.
- The motor does not get hot, since it draws current proportional to load.

- Usable in high speed torque. Maintains rated torque to 90% of unloaded RPM.
- It is quiet at high speeds.
- Resonance and vibration free.

Of course, there are also disadvantages:

- They must be driven by a controller to time which coil receives power. These controllers are expensive.
- An encoder is needed to measure the position and give this information to the controller.
- Motor itself is expensive due to permanent magnets.
- Back EMF must be accounted for.

This makes this motor more expensive to drive, but the possibilities with high torque at high speeds and inertia is exactly what is needed for this project.

A motor that would be mountable on the legs, can not be too large or heavy. The BLDC Motor HPM3000 from Golden motor technology is 25cm*25cm*26cm and has a weight of 8kg. This is already quite bulky, so larger motors are only usable if they would be mounted around the waist. They have a rated torque of 10 Nm and can run on a speed of 3000-5000rpm depending on the voltage (48V – 72V) [34]. Since BDLC motors are known to maintain their rated torque to 90% of unloaded RPM [33], we will calculate with 4000 RPM to build a safety margin.

If this is not enough, the option of using more bulky motors at the base around the hips will be considered.

In the calculations in Chapter 7 will be done both for the stepper motor and BLDC motors, since stepper motors would be a much cheaper solution if those would be enough.

4 TARGET MARKETS

Since the development and construction costs will probably not make a final product for less than €5000, but much more, the initial focus will be on selling to companies. Examples of companies that can be interested in this technology are:

- Companies that use simulations for field trainings, such as fire-fighters, police and military simulations.
- VR-exo will also be valuable in medical environment to help and motivate people to walk again that suffer from paralysis or other injuries.
- VR-exo is highly suitable for the game industry. VR arcades are popping up more and more. Only in the Netherlands there are currently 26 VR-arcades, of which six already use VR-treadmills.
- Potentially theme parks that want to offer unique rides.

5 REQUIREMENTS VR-EXO

Since the many complaints about how the walking feels on the treadmills and slide-mills, this will be a top priority in this design. If it does not feel right and natural, this will hurt the reviews a lot and therefore reduce the success of the product. The other concerns are the price and the size. This is especially important during transport (see Section 2.3). It should therefore be kept as light, compact and cheap as possible.

The requirements are split in must haves, should haves, could haves and would haves. This arrangement is not final. A proper market research is needed to determine the most important features.

5.1 MUST HAVES

- The user must be able to put down a foot and feel that his foot stops mid-air as if it were floor. This should be possible for stepping on and off stairs, walking up and mountains, etc. This involves being able to lift the knee at least to hip height. And being able to rotate around the ankle to provide final inclines of about -45° to 45° relative to the floor.
- The construction should keep supporting the foot while it is on the 'floor' during the full walking motion.
- After each walking motion, the user should be back within the same area.
- There should be built in restrictions to provide natural stops, so the user cannot be injured if the construction bends the joints in the wrong way or experiences too fast sudden movement.

5.2 SHOULD HAVES

- The motion should feel as natural as possible.
  - The foot should move across the virtual 'floor' in a straight line in normal walking.
  - The foot should be stopped instantly when hitting the virtual floor, lower than the brains threshold for accepting feedback.
- The feet are supported from a construction fixed around the waist of the user. This makes future models more adaptable in rotation.
- The construction should be able walk, but the construction should be able to handle running forces up to 5 m/s (= 18 km/h). These forces are covered in Section 6.2 and 6.3.
- The construction should be as affordable as possible.
- Users from at least 1.20m to 1.90m should be able to use the construction.
- Weights up to at least 100kg (preferably 150 kg) should be supported.

5.3 COULD HAVES

- The user should be able to lift his leg for a minimum of 90 degrees.
- The friction on the 'floor' should feel like walking on a treadmill or like on a solid floor, not like sliding across it, which is the case with slide-mills (see Section 2.3).
- The user should be able to run within the construction with at least 5 m/s (= 18 km/h).
- The construction should be foldable for easy transport and storage. This is important as stated in Section 2.3.1. If possible, it should be able to be lifted by two people and should fit through doors without problems.
- The construction fully expanded should fit in maximum about 10 m^2 and should with the user inside not be higher than 2.3 m (ceiling height in the Netherlands is around 2.4m for living rooms) [33].

5.4 WOULD HAVES

- The user can sidestep while walking.
- The user can turn around while walking.
- The user can jump.

- The user can be tilted on his side.
- The user can be tilted forwards and backwards.
- There is not only force feedback on the legs, but also on the arms.

6 THE BASE OF THE PROBLEM

The construction problem can all be scaled down to one main problem. The first proof of concept focusses at moving forward only, therefore leg of the user will move in a 2D plane, see Figure 20. Since the user will move his own legs to walk, it suffices to distill the problem to only moving and stopping the foot when it hits a surface in VR.

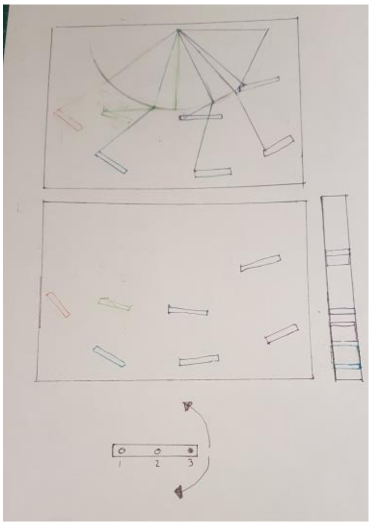

Figure 20: The base of the problem. The foot of the user should be able to be moving and stopping within a certain defined area. The foot should also be able to tilt left or right to be able to accommodate all positions.

6.1 WHAT MOVEMENTS SHOULD VR-EXO BE ABLE TO MAKE?

If the user does not touch an object or floor in VR, the foot of the user should move as freely as possible, without pushing through motors or feeling much resistance or weight pulling down on the foot. When the user encounters an object in VR, the foot should be stopped mid-air from entering the object but must still be able to move freely away from it (e.g. upwards if the foot is on the floor). The foot must also be able to tilt a certain amount. The natural angles of the ankle can tilt about 0 to 45° downwards and 0 to 20° upwards with respect to the lower leg [34]. The rotation of the ankle is not per definition coupled to wat the VR-exo can do. The users foot will only be attached by the toes, meaning that the user kan lift the heel and bend his ankle during walking already. The reason why the platforms should still be able to tilt, is that the user should be able to walk on inclines or declines. Since the user cannot bend the foot downwards more than 45°, inclines more than that would not be safe. Inclines upwards however, can be higher, because the user can walk on his toes. Rotations from approximately -45° to 45° should be possible with respect to the user. That does not determine the rotation with respect tot the exoskeleton, see Figure 27.

Since the movements should be in a 2D plane only, the movement in the third dimension should be blocked for stability. The construction that blocks this movement from happening, can be adapted at later iterations of the project to tilt the leg and make sideward movement possible. An example solution can be fixing a rod to the foot which is locked between to bars, so it can only move vertically. Another option is to make a second skeleton next to the legs. This las option is currently drawn in most of the designs.

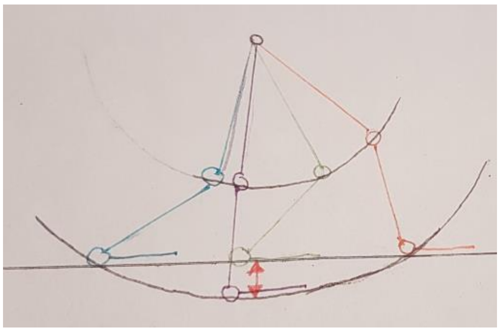

Figure 21: To make the movement feel natural, the foot should move in one horizontal line across the 'floor'. This means, the foot should be lifted mid-step by the construction. This figure does not represent an accurate gait of walking or running but is made to illustrate the problem.

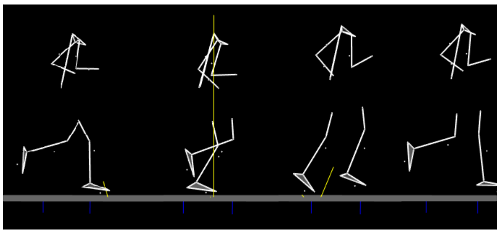

Figure 22: A motion capture by MotionLab, visualized in Mokka software of a running motion on a treadmill. The yellow line represents the force. From left to right: touchdown, most force present, last contact moment and maximum swing floating.

When the choice would be to at least create an extra skeleton near the legs, the situation in Figure 21 would occur. The exoskeleton foot would move in a circular motion, while the actual motion of the foot should be horizontal. This means that the foot should be lifted mid step to make the movement fully horizontal.

6.2 WHAT FORCES AND SPEEDS SHOULD IT BE ABLE TO HANDLE VERTICALLY?

There are many possibilities in achieving these movements mechanically, although the freedom of motion that should be achieved, is less easy. Even more so, are the large forces that the construction will experience. For this initial design, the maximum mass of the user will be set on 100kg, which makes the gravity force around 1000N. When the user jumps vertically, this force can increase up to six times to body weight (see Section 3.3.1) [35]. This would correlate to 6000N on the construction. However, for this proof of concept, this force will not be considered. During running up to 18 km/h, the forces get no larger than about 3200N (see Section 3.3.1). While the foot touches the 'floor', the foot must lift by the construction (see Figure 21). Mid-step, the forces are about 3200N as well, which means that the construction should be able to actively lift a force of 3200N vertically. It needs to be lifted within approximately half a step. The step contact time at a running speed of 5 m/s is 200 ms [26]. The running gait is not symmetric, but approximately this means that it needs to be lifted within 100 ms. How much the feet should move up and down is not easy to determine and based on the movement pattern of an individual person. For a walking motion this was determined from Figure 23 for the longest leg that should fit VR-exo (1086mm (see Section 3.3)) at a height difference of 46mm.

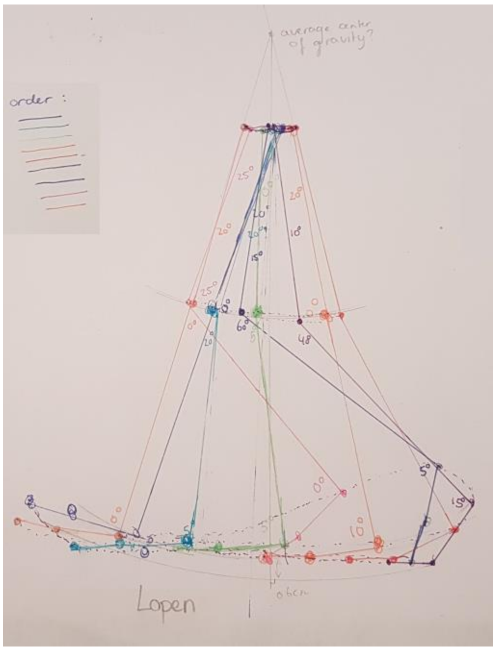

Figure 23: Gait analysis of walking drawn in one image from this video. For a hip height of 1086mm (see Section 3.3) the height difference (Δh) with respect to a circle movement, was determined to be 46mm from measuring the drawing at scale.

6.3 WHAT FORCES AND SPEEDS SHOULD IT BE ABLE TO HANDLE HORIZONTALLY?

If the user is moving forwards with 5m/s, this means that the floor is moving with 5m/s with respect to the user. This means that the footholds should also be able to move back with 5 m/s. The horizontal maximum breaking force of stopping abruptly during a 3 m/s run, were determined to be 2 times the body weight horizontally as maximum within 600 ms of a single foot break. The participants were approximately 70 kg [36]. This is equivalent to F =70 kg * 3 m/s / 0.6 s = 126N. From this video it is evident that the acceleration forces for sprinting are much higher. The maximum force for the horizontal component in this video is approximately 750N. This is not said to be the maximum forces that the construction will endure, since the test subject was not 100kg, but it gives a good approximation.

6.4 WHY NOT SUPPORT THE FEET FROM BELOW?

This proof of concept model will not include rotation. However, the reason that in all current designs the legs hang from a ring, instead push up from under the foot is: if the user is to be tilted backwards/forwards and left/right in later models, it is easier to have all the constructions attached to one point.

Not all possible rotation techniques will be discussed, but only a few to show the attachment is important in a large variety of solutions. One possible (but very colossal) solution is to make the user (purple in Figure 24) hang within a few rings. To do this, the pressure plates to push back under the feet, should be connected near a construction at the centroid of the user, so the entire construction can easily rotate around one point. The second option is more compact (Figure 25). This also requires the construction to be attached at a point at the waist.

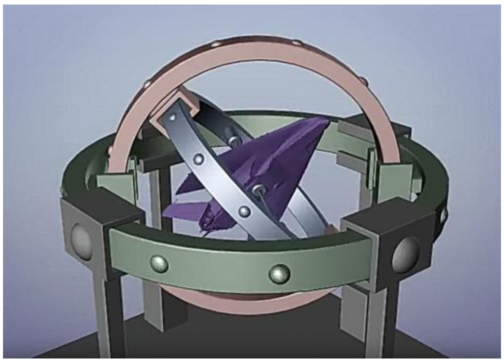

Figure 24 shows a ring construction to rotate a user in multiple degrees of freedom. The purple part representing the user. (Animation).

Figure 25 shows a more compact design wherein the user can be rotated in most degrees of freedom as well. Both need a fixed point to rotate the person. It makes the most sense attaching it near the centroid of the user, near the hips.

7 CURRENT DESIGNS

There are many options creating a construction conform the requirements, however each one has its advantages and disadvantages. It would be the most convenient to be able to calibrate the construction to fit any length by software only. This eliminates having to adjust the leg lengths before a new user steps into the construction, which makes applications where multiple users should fit easy. Therefore, the construction lengths are considered fixed in the current designs. The base skeleton of most designs is visible in Figure 26. This figure shows the legs of the smallest person that should fit in blue and the construction in orange. The construction has approximately the same length as the longest users legs. The only difference, is that the skeleton does not have a toe joint. This means that if a person of the same size as the skeleton walks in it, it will not fit during the foot lift phase (see Figure 28). The red semi circles here show that the exoskeletons lower leg is not long enough to join the exoskeletons thigh. This is ignored in the following drawings and calculations.

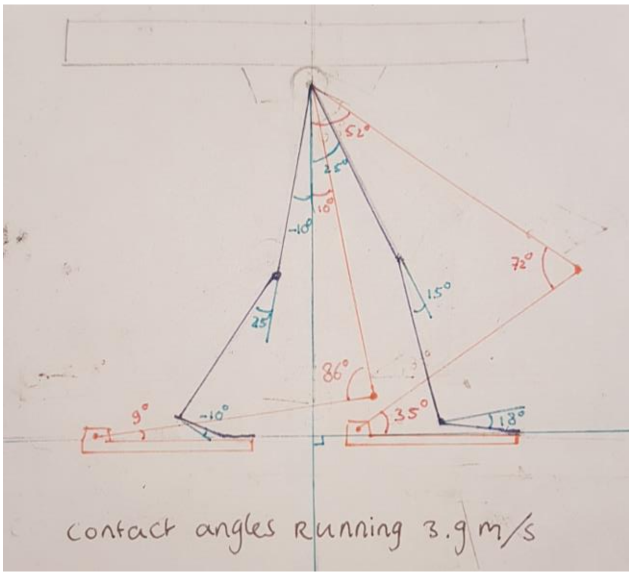

Figure 26: Blue represent the angles of the joints at just making contact and just before releasing contact at a running speed of 3.9m/s, See Section 3.3.3. It has been drawn on scale with a total leg length of 68 cm (shortest person that should fit VR-exo). The orange lines are the size of the construction, based on the longest legs that should fit (108cm).

Since this project is still in diverging phase, all posibilities that can be thought of are evaluated, to make the best choice possible.

Some solutions have the slight disadvantage that with moving the foot upwards, the user encounters resistance of the motors. This problem occurs in all options except for some pneumatics and rolling in and out cables. The upside of solutions that have this disadvantage is that springs or elastic bungee cords can be attached to alleviate half of the forces, so they only have to carry 1600N in stead of 3200N. If that would be done with for instance steel cables, the user would feel a constant pull of 1600N under his foot, which would roll in the cables all the way, with or without user. Therefore, only at linear actuators will be calculated with 1600N.

7.1 MOTORS ON THE SKELETON JOINTS (LIKE THE AXONVR SUIT HAS (SEE CHAPTER 2.4.2)).

This would make the slimmest exosuit, but the forces on the motors are relatively large. This concept should fit leg lengths from 68 to 109 cm (see Section 3.3.2). When the user runs, the angles at touchdown and foot lift will approximately be as in Figure 26. [37] The contact time of the feet while running 5 m/s is 200 ms. [26] This means that when the motors would be placed on the hip, knee and joint like on the AxonVR suit (see Section 2.4.2), it should be able to turn at an RPM so that the angles from touchdown to foot lift can be reached in less than 200ms. In Figure 26 the figure has been drawn for the smallest person. However, for the largest person, the angles of the construction will be more or less the same as for the angle of the persons joints. Therefore, the blue angles will be considered the angles for the largest person that fits the construction and the orange angles will be used for the smallest person that can fit the construction. These angles wil be used for the calculations in Table 1. The rotations per minute (RPM) can be calculated with Equation 1.

Equation 1: Calculation of RPM for a certain rotation of a motor in degrees.

$$rotations/min\ (RPM) = \frac{|\,degrees\ touchdown\ -\ degrees\ foot\ lift\,|\ /\ 0.2s}{360°/\ rotation} * 60s/min$$

Table 1: The RPM calculations based on the angle differences from touchdown to foot lift.

Joint	Difference largest person (blue) (°)	Difference smallest person (orange) (°)	Maximum difference (°)	RPM required for max difference
Ankle	28	26	28	23.3
Knee	10	14	14	11.7
Hip	35	42	42	35

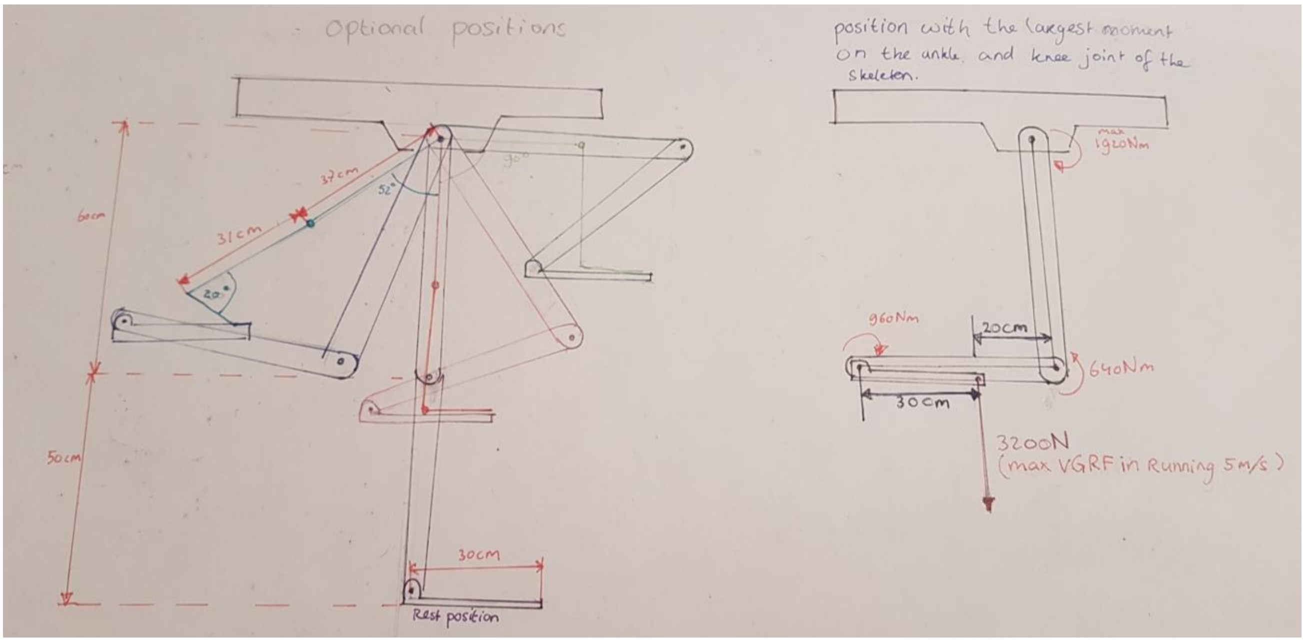

Figure 27: Left shows some optional positions the exoskeleton should be able to take if the smallest person should be able to fit. This makes the orientation for the maximum forces seem plausible to exist. For the maximum vGRF (3200N for 100kg) for running at 5 m/s [25], this would put 960Nm and 640Nm on the ankle and knee motor respectively. The position for the maximal hip torque is drawn in green on the left and would provide a torque of 1920Nm on the hip motor.

7.2 STEPPER MOTOR CALCULATION

The peak performance of the JVL heavy-duty stepper motors in Figure 19, is at maximum 1500 RPM (for 310V so for 220V even less). This gives a torque of approximately 7.5Nm. With a harmonic drive or other gear system, the speed can be reduced to increase the torque linearly. For the ankle, the minimum RPM at which it should turn is 23.3 RPM. 1500RPM / 23.3RPM gives a maximum gear ratio of 1:64.3 to not reduce the speed below minimum. This would increase the torque to 7.5Nm * 64.3 = 483 Nm. Given that it should be able to hold 960 Nm, it is not possible to lift the toe at 5 m/s running speed and forces. This is cannot be achieved with any gear ratio in combination with these motors. The other RPM to torque values in Figure 19 give lower final torques.

There are options to lighten the load, such as a spring within the joint that always pushes the toe up with 480Nm. This would reduce the torque the motor has to deliver at its peak to 960Nm – 480 Nm = 480Nm, which would make it barely feasible with a maximum torque of 483Nm. This would push the motors to their limits constantly at 310V, which is not a good idea.

The hip joint for example, requires even higher torques vs speed ratios. The maximum gear ratio is 1:43, which gives a maximum torque of 323Nm, while a torque of approximately 1920Nm is needed. This is not fixable with a spring, since the difference is more than two times the maximal possible torque. As a solution, multiple motors per joint can be used, but they must rotate at exactly the same speed to not to rip apart the construction.

Since I have not been able to find higher torque vs speed motors, this mechanical solution is not deemed possible with stepper motors.

7.3 BRUSHLESS DC MOTOR CALCULATION

7.3.1 THE ANKLE

Similar to the stepper motor calculation, the ratio would be: 4000 RPM / 23.3 RPM = 1:172 to reduce the speed to the minimum needed. This would increase the torque to 10Nm * 172 = 1720 Nm. This would be more than enough to accommodate the torque needed at the ankle. With a spring to lighten the load, this would be even considered a huge overkill, since it would only have to carry 480 Nm.

7.3.2 THE KNEE

Estimating that the force will be present at 40cm from the rotation point at maximum, the torque will then be 0.4m*3000N = 1200Nm. The ratio to reduce the motor RPM to the minimum RPM needed is: 4000 RPM / 11.7 RPM = 1:341. The torque that this would make available is: 10Nm * 341 = 3410 Nm. This would therefore be easily possible as well.

7.3.3 THE HIP

The maximum extent will probably not be more than the length of the upper leg part plus the length of the foot. This would be 90 cm. 80 cm would be a good approximation, because the knee is always less than 90 degrees during the impact while running. This means that the torque the motor should be able to reach is 0.8m*3000N = 2400Nm. The ratio for the minimum speed needed is 4000RPM / 35RPM = 1:114. The motor would be able to reach a force of 114 * 10 Nm = 1140 Nm. This is not enough. But since this is at the base of the construction, adding a larger more powerful motor would not be an issue.

7.4 MOTORS THAT ROLL CABLES CONNECTED TO THE SKELETON IN AND OUT.

This would be a solution to pushing through the motors when moving the foot upwards. Since the cables only pull when the foot moves downwards, the upwards motion is free, this will provide a more natural feeling of walking. It may be that this does feel less solid than the other solutions. Thereby there must be found a solution to make sure that in this prototype, the feet cannot move off the 2D plane.

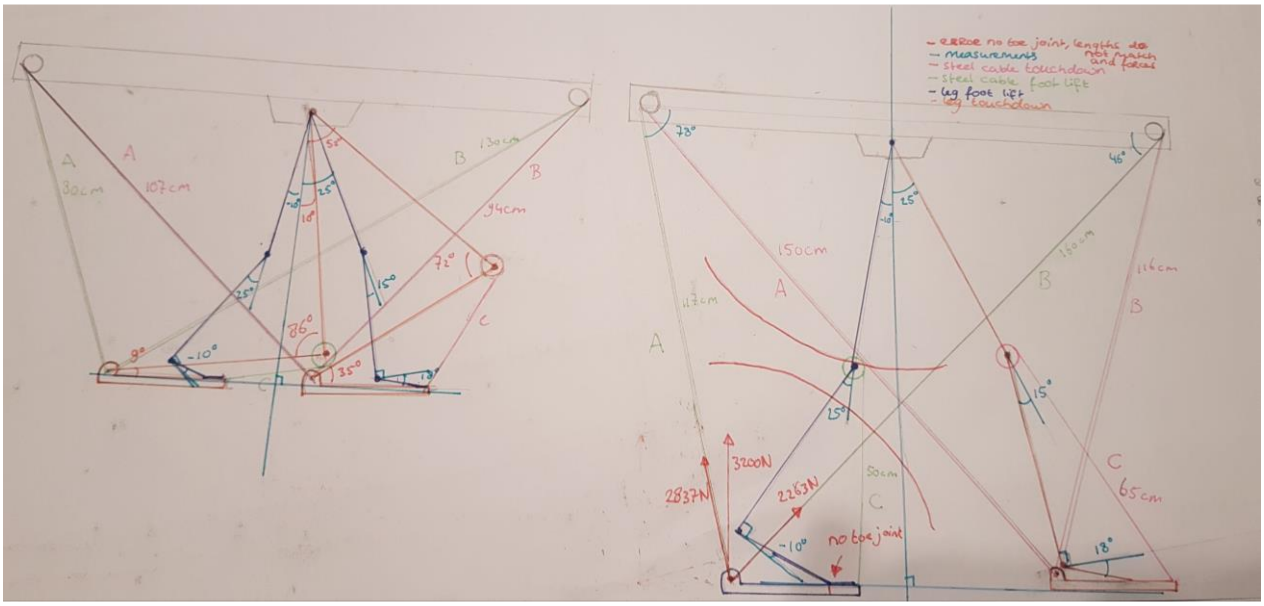

Figure 28: The angles on touchdown and foot lift, See Section 3.3.3. From this can be calculated that the maximum force on the left position will be around 2850N if only the vertical force is considered (see Appendix A 9.1). (The 3200N is shown in the opposite direction on the image.) The lengths of the cables differ at most with 160cm – 116cm = 44 cm.

Figure 28 shows the forces which are present on the motors in the foot lift position. The maximum force in this position is around 2850N (see Appendix A 9.1). If the spool would have a radius of 5cm, this would give a torque of 143Nm. The length that a cable should shorten in one step of 200 ms (see Section 3.3) is 44 cm. The motor would have to turn 44cm/5cm = 8.8 RPS = 528 RPM. At this RPM, the torque of the JVL motors is about 32.5Nm, see Figure 19. This is not nearly enough for 143Nm. For 1 cm, the torque would be 28.5Nm, and the RPM would have to be 2850. The graph shows that this is once again not possible. To make matters worse, this is a larger hassle for Figure 29.

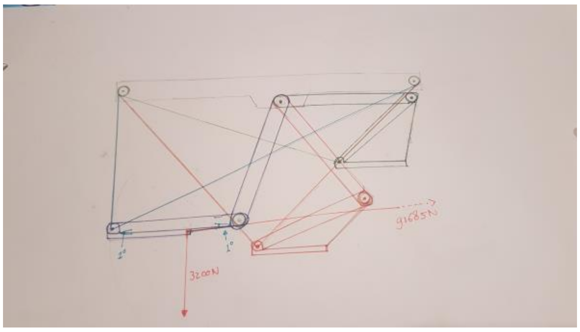

Figure 29: The same positions as in Figure 27 except for blue. Since the toe is lifted towards the knee by the cable, the toe cannot rotate past the 'shin' part of the exoskeleton like in Figure 27. This limits the rotation past the blue exoskeleton drawn. Even then at a 1° limit, the force is too large (92000N) towards the motor (see Appendix A 9.2). The real angle limit will therefore be even lower in this construction.

In Figure 29 the same example orientations as in Figure 27 are shown, with the exception that the blue position is different, because the cable from the knee pulling up the toe can not support negative angles. Thereby, even the corners of 1° drawn cannot be supported by the motor. Putting 3200N on there, which is the maximum vGRF while running 5 m/s, will need a force of 92000N on the rope (see Appendix A 9.2). This would limit the possible angles severely, although this construction already had problems since Figure 28. Since these extremities of forces cannot simply be pulled by even larger motors, this solution is probably not the best solution.

7.5 HYDRAULICS/PNEUMATICS

Another option where in addition to motors, is hydraulics or pneumatics. An example is given in Figure 30, however this still has the same problems with the motors hauling up the steel cable in Section 7.4. Thereby, there are some collision problems with this concept, see Figure 31.

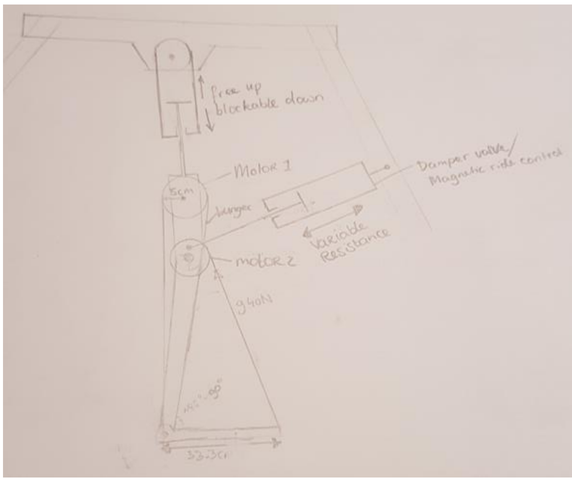

Figure 30: An option where pneumatics or hydraulics are used in addition to motors. The horizontal damper valve can have magnetic ride control to control the resistance across the floor. The pneumatic cylinder can move free upwards, to not hinder movement during the lifted phase of the step but can be blocked in the downward direction.

Hydraulics can handle higher forces than for instance linear actuators. However, it is hard to find at what speed those forces can be lifted. Another advantage of this construction is that it can apply a constant force without the pump having to supply more pressure. Downsides are that there is always a resistance when the user wants to lift his foot. Thereby they are hard to control accurately and suffer from 'stick slip', which would cause the foot to jolt and jerk in transition to being still and moving. Thereby, regular maintenance is required to avoid leakages. [38] Hydraulic or pneumatic solutions have not been researched in depth yet.

7.6 LINEAR ACTUATORS INSTEAD OF HYDRAULICS/PNEUMATICS

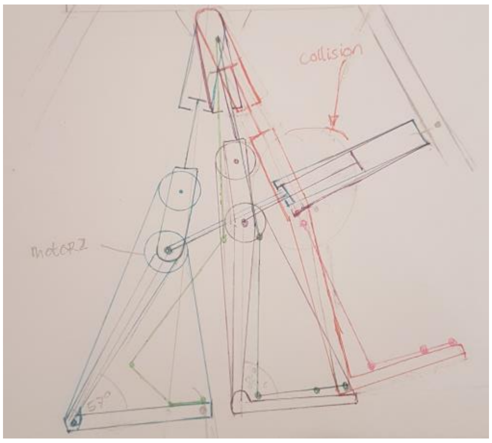

Figure 31: During walking motion, the horizontal hydraulic cylinder creates a collision with the leg.

The precision and speed of linear actuators is very good. The speed is easily controllable and good. There is no risk of leakages, which means less maintenance. This reduces costs as well. Setting it up is easier than with hydraulics, which requires external pumps or motors. This also makes the total units smaller. For safety, they would also be preferred since they can lock themselves in place during a power failure. They can, however, overheat when left running for too long. [38] They have the same problem as hydraulics, in that if the user wants to move his foot upwards, he will have to push through the resistance of the motors, which does not give a natural feeling. Not many sketches containing linear actuators have been made yet. They do however, have the same limit as stepper motors. These limits have been found calculation for the linear actuators as if they were in place of the steel cables from knee to toe in solution 7.4. Linear actuators that can deliver 15 cm/0.2 seconds at a force of 1600N are nowhere to be found. Linear actuators that advertise to work heavy-duty have typical speeds up to 68mm/s with a 1700N maximum load. [39] It should be 10 times as fast to make this possible. Of course, using a BDLC motor to make a linear actuator could do something. This would have the same effect as using gears to limit the rotation speed of the motor. James Bruton uses BLDC's this way for his Open Dog and other bipedal robots [42], although they are much lighter. It should be theoretically possible to do this if a design with advantages would require this.

7.7 CHAINS ROTATING AROUND GEARS TO MOVE THE FEET PLATEAUS UP AND DOWN.

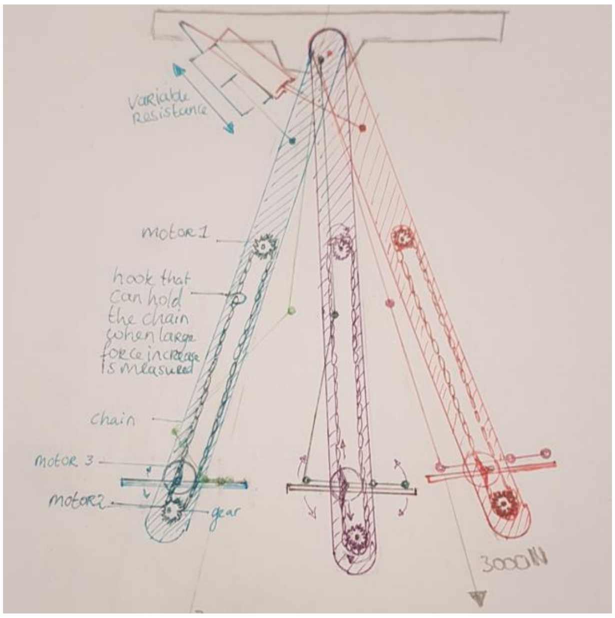

Figure 32: A solution where the forces are largely caught by the construction itself. The chain which moves the foot plateau up and down, can be locked during forces larger than the motors can handle. There will be a slight height difference during the swing of the step with the height motor locked. Motor 3 must still be active to rotate the platform horizontally.

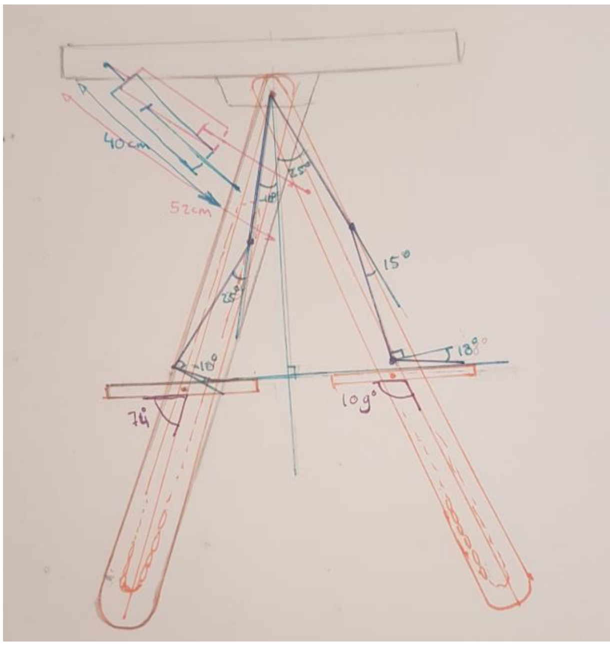

Figure 33: The angles during touchdown and foot lift are drawn. See Section 3.3.3. The angle difference for motor 3 is 109 – 74 = 35°.

This is a way to make a completely straight construction near the leg to make relatively large up and down motion of the foot plateau possible. The chain can be rotated by two motors, dividing the forces. Thereby this needs an additional solution for the horizontal component and the potential turning of the foot plateau. It is a relatively simple design as well. A disadvantage can be that the chain is noisy. In this design, it is an option to lock the chain in place when a force that is higher than the motors can handle is measured. The motors would then experience no force. Motor 3 is needed to rotate the platform to keep it horizontal. This cannot be locked since it would otherwise describe a circular motion. The motor can be placed in the middle of the foot, which reduced the torque on the motor by half, making the arm 15cm. If on the toe a force of 3200N is applied, the torque would be 3200N * 0.15m = 480 Nm.

The amount of rotation in one step, 200 ms, should at least be 35°, see Figure 33. The minimum rotation speed can be calculated with Equation 1 to be 29 RPM. The 7.5 Nm for 1000 RPM in Figure 19 can be converted with a gear ratio of 1:34 to be 257Nm at 29 RPM. This is once again not enough, but with a spring to pull the plateau to the middle position, some load can be lifted, and more careful placement of the foot can place the load closer to the rotation point. If the 3200N can be near 8 cm of the rotation point, the motor would be able to handle the force with 257Nm. Of course, if a brushless motor is used, this would be even more easy.

7.8 OTHER OPTIONS

There are many options that were not considered yet. More research should be done in options for hydraulics or pneumatics despite their disadvantages. Another option includes trying to scale the technique used by DextrES (see Section 2.4.4) and use this in addition to current methods. This could in theory support up to 800N, see Appendix B 10. It may be a disadvantage that the layer between the metal plates is very thin (32 µm polyamide) and may wear down fast. If there is a short circuit due to this, that would certainly not be good. However, if a solution can be found to this problem, it might give a very compact solution.

8 CONCLUSION

Not being able to set foot in the infinite virtual space is a limitation in the current VR technology. Current software solutions to cope with this different space mapping include teleportation and locomotion. Teleportation does feels less immersive, for you appear suddenly at a certain spot, instead of walking there. Locomotion is a smooth movement in the VR world controlled by a joystick or trackpad. This, however, induces motion sickness. To solve these problems and increase immersion in VR, multiple companies have made omnidirectional treadmills and slide mills. They solve some problems, but treadmills have problems with their size and inertia to change a direction. Slide mills suffer from not feeling the right friction, making it feel like ice skating on bowling shoes. Both only provide walking on a flat surface. AxonVR is currently working on an exosuit, similar to what VR-exo should be capable of. However, in their video, it is a very slow unsteady movement. Since they seem to think in one design only, the vision of VR-exo is to see if there is an option that would support these forces in another way and make a solution that would be better than the AxonVR suit. A solution in which people cannot only step onto things slowly but can run. Thereby, different sizes of people should fit, which does not seem possible with their current solution.

The following options have been discussed: Motors on skeleton joints, motors that roll cables in and out, hydraulics/pneumatics, linear actuators, chains rotating around gears to move the foot plateau up and down and very briefly the option to scale the mechanism of the DextrES glove up to leg scale. Not close to all the options have been considered, but most of the current designs have problems handling the vertical 3200N that is present when a person of 100kg runs 18 km/h. Brushless DC motors are able to handle those forces, so in theory this would be possible. The largest forces possible have not even been considered, which would be near 6000N for the landing of a vertical jump. Therefore, jumping is considered a could have, for later. Some options can passively support the 3200N, by blocking the vertical movement, such as the chains rotating around gears option. The most logical option of motors that are directly positioned on the joints should work as well. There are still many undiscovered other options, which are still being researched.

9 APPENDIX A: DIVIDING 3200N OVER TWO STEEL CABLES

9.1 FOR 78^{O} AND 46^{O} (FIGURE 28)

F_A*cos(78) - F_B*cos(46) = 0

F_A*sin(78) + F_B*sin(46) - 3200N = 0

Force in cable B (F_B):

F_A = F_B*cos(46)/cos(78)

F_B * cos(46) / cos(78) * sin(78) + F_B * sin(46) - 3200N = 0

F_B * 0.69465837 + F_B*0.7193398 = 3200N

F_B = 2263N

Force in cable A (F_A):

F_B = F_A * cos(78)

F_A* sin(78) + F_A * cos(78) * sin(46) - 3200N = 0

F_A * 0.978147601 + F_A * 0.149559154 = 3200N

F_A = 2837N

9.2 FOR 1^{O} ANGLES (FIGURE 29)

F_A*cos(1) - F_B*cos(1) = 0

F_A*sin(1) + F_B*sin(1) - 3200N = 0

F_B = F_A * cos(1)

F_A *sin(1) + F_A * cos(1) * sin(1) = 3200N

0.034902155 * F_A = 3200N

F_A = 91685N

10 APPENDIX B: UPSCALED DEXTRES FORCES

$$F_{compression} = \frac{\epsilon_r \epsilon_0 A V^2}{2d^2},$$

With ε_r = relative permittivity of the insulator between the electrodes, ε_0 the permittivity of vacuum, A the overlap area between the electrodes, V the voltage and d the thin dielectric gap between the electrodes.

$$F_{friction} \leq \mu F_{compression}.$$

The friction that this compression causes, is the friction coefficient μ times the compression force.

From this, we can calculate that the compression force with the values they used would be:

$$Fcompr = \frac{3.4 * 8.85419 * 10^{-12} C / V\ m\ * 11 * 10^{-4} m^2 * (2000V)^2}{2 * (32 * 10^{-6} m)^2} = 64.7N$$

The friction force measured was more than 20N. μ = 20N / 64.7N = 0.309

$$Fcompr = \frac{3.4 * 8.85419 * 10^{-12} C / V\ m\ * 0.044 m^2 * (2000V)^2}{2 * (32 * 10^{-6} m)^2} = 2587N$$

$F_{friction}$ = 0.309 * 2587N = 800N.

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