



Investigating the User Experience of Virtual Reality Rehabilitation Solution for Biomechatronics Laboratory and Home Environment

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Virtual reality (VR) technology is a promising tool in physical rehabilitation. Research indicates that VR-supported rehabilitation is beneficial for task-specific training, multi-sensory feedback, diversified rehabilitation tasks, and patient motivation. Our first goal was to create a biomechatronics laboratory with a VR setup for increasing immersion and a motion platform to provide realistic feedback to patients. The second goal was to investigate possibilities to replicate features of the biomechatronics laboratory in a home-based training system using commercially available components. The laboratory comprises of a motion platform with 6-degrees-of-freedom (Rexroth eMotion), fitted with a load cell integrated treadmill, and an Oculus Quest virtual reality headset. The load cells provide input for data collection, as well as VR motion control. The home-based rehabilitation system consists of a Nintendo Wii Balance Board and an Oculus Rift virtual reality headset. User studies in the laboratory and home environment used direct observation techniques and self-reported attitudinal research methods to assess the solution's usability and user experience. The findings indicate that the proposed VR solution is feasible. Participants using the home-based system experienced more cybersickness and imbalance compared to those using the biomechatronics laboratory solution. Future studies will look at a setup that is safe for first patient studies, and exercises to improve diagnosis of patients and progress during rehabilitation.

Keywords: virtual reality, biomechatronics lab, physical rehabilitation, user experience, home system

1 INTRODUCTION

Virtual reality (VR) is a promising tool in the rehabilitation of neurological conditions, such as stroke, Parkinson's disease and traumatic brain injury (Cano Porrás et al., 2018). Patients with neurological conditions often require rehabilitation in the early stages, and some require rehabilitation regularly throughout their lives. Problems with balance and gait are some of the challenges which often limit these patients in everyday life (Darekar et al., 2015). Generally, patients undergo rehabilitation at a facility and follow self-guided rehabilitation programs at home. In the last decade, research has focused on increasing motivation by creating multi-sensory VR rehabilitation programs (Cano Porrás et al., 2019). This is because research has shown that, especially self-guided programs, can be tedious and demotivating (Howard, 2017; Koenig et al., 2019). The inclusion of

tools such as treadmills, motion platforms, and sensors aims at creating more fun, effective, and task-specific rehabilitation programs (Shema et al., 2014; Kern et al., 2019).

A collaboration between teams with experience in multimedia technology and mechatronics engineering developed a prototype of a biomechanics laboratory at the University of Agder. The biomechanics lab consists of a 6 degrees of freedom (6DOF) Rexroth motion platform, a treadmill integrated with sensors and a virtual reality headset. A home-based system was developed as a prototype for exploring the possibility of using the system at home (Madshaven and Markseth, 2020). We implemented the system through a human-centred design process including stakeholder involvement and user-based testing. The prototypes were developed as a proof-of-concept as a starting point for future development. This research was conducted on healthy adults. The long-term motivation for the research is aimed at rehabilitation of balance and gait problems in patients with cognitive impairment.

The paper is organized as follows: A review of the research work regarding the possibility of improving rehabilitation using VR is given in **Section 2**. In **Section 3**, the realization of a biomechanics laboratory platform. In **Section 4**, a simplified home version of the platform is presented. User tests and preliminary results are showcased in **Section 5**. Finally, proposed future work and planned activities are discussed in **Section 6**.

2 TECHNOLOGY SUPPORTED REHABILITATION

2.1 Rehabilitation and Virtual Reality

Physical rehabilitation helps people who have difficulties with gait, balance and mobility towards living a normal life. Therapists create an individual plan for each patient that may include massages, balance and gait training, pain management, etc.¹ A program can focus on various exercises, such as stability and strength, balance, gait etc., and the number of repetitions depending on the patients capacity. Starting with a small number of repetitions and slowly and steadily increasing the number (Stoek et al., 2016). Many patients need treatment in a medical facility and a long-term self-guided rehabilitation program (Lawo and Knackfuß, 2018). Patients often struggle with keeping up the motivation when having to exercise regularly alone Koenig et al. (2019), resulting in low adherence to self-guided programs (Proffitt and Lange, 2015; Kleim et al., 2019).

VR has a potential of creating specific task-related training scenarios for situations that could be impossible or even dangerous for patients to perform in real life (Weiss et al., 2003; Holden, 2005; Brtsch et al., 2010; Kalron et al., 2016). VR has been used in the rehabilitation of several medical problems, and VR design varies from game-like activities (Gil-Gmez et al., 2011; Seo et al., 2016) to task-specific everyday activities such as kitchen work (Koenig et al.,

TABLE 1 | Human senses considered for VR rehabilitation.

Senses	Feedback	Tools
Proprioception	Movement	Motion platform
Vestibular	Movement	Motion platform
Sight	VR environment	VR headset
Hearing	Music, talking, ambiance etc.	VR headset

2019), grocery shopping (Kizony et al., 2010) or simply crossing a street (Weiss et al., 2003). These task-specific exercises are especially beneficial for patients with cognitive impairments (Lawo and Knackfuß, 2018). With VR, patients interact with a computer-generated world while doing rehabilitation exercises. Virtual reality rehabilitation (VRR) has been shown to improve problems with balance, gait, motor control and strength (Howard, 2017), even more so when combined with traditional rehabilitation (Cano Porrás et al., 2018). Utilizing VR in rehabilitation has been shown to have benefits for both patients and therapists. A therapist evaluates each environment's safety, controls what stimulus patients receive during an exercise in the environment, and chooses what the patient can interact within the virtual environment, such as other people or objects (Schiza et al., 2019; Lubetzky et al., 2020), while training in a safe environment.

According to Howard (2017) and Cano Porrás et al. (2018), using VR in rehabilitation increases motivation, the feeling of enjoyment, and adherence to the program. Using VR in rehabilitation offers individual adaptation (Koenig et al., 2019), since VR offers a vast amount of design possibilities. With individual adaptation, the exercises and environment can be designed to fit each patients needs and capacity. Studies show that conventional rehabilitation exercises can be transferred to VR (Proffitt and Lange, 2015; Kern et al., 2019). It also opens up the possibility of home-based rehabilitation programs. What motivates and interests a person varies between individuals. By using the benefits of VR, individualization of rehabilitation programs can be created to suit each patient. For example, a person post-stroke may be interested in fishing but, due to health challenges, can't go fishing until enough mobility in the arms is regained. By using VR, it is possible to create a fishing game that would be fun, motivating and support the rehabilitation of such patients. Fun and immersive VR exercises could appeal to each individual better than the repetitive execution of abstract movements without any feedback and enjoyment that VR can potentially offer (Keshner and Fung, 2017).

VR has the potential to give multi-sensory feedback (Cano Porrás et al., 2019), such as sight, hearing, and movement to make the experience more immersive, engaging, and motivating for the patients (Kourtesis et al., 2019). **Table 1** presents the different senses along with the feedback and the tools that display or creates the feedback. The two primary senses are used to monitor the external environment while the proprioception and the vestibular sense are related to the body's awareness of position, movement of limbs and muscles, and balance (Tuthill and Azim, 2018). To facilitate changes in proprioceptive cues different surfaces, some of which are mentioned in chapter 2.2 could be used.

¹Integris (2018). A Guide to Different Types of Rehabilitation Therapy, <https://integrisok.com/resources/on-your-health/2018/may/a-guide-to-different-types-of-rehabilitationtherapy>.

2.2 Motion Platforms and Sensors in Rehabilitation

Tools such as camera-based systems, treadmills, force plates, and motion platforms can enhance rehabilitation exercises. For example, the CAREN² (Computer Assisted Rehabilitation Environment) system is a biomechanics lab, consisting of a treadmill mounted on a 6 degrees of freedom motion platform and a dome that projects a virtual environment. The lab, created by Motek Medical,³ adds the benefit of ground movement, such as when walking down a slope or standing on a ship at sea. CAREN has proven to be an effective method in balance training (Kalron et al., 2016) for rehabilitation of people with multiple sclerosis, as well as in rehabilitation of gait and balance problems (Sessoms et al., 2015; Cano Porrás et al., 2019).

A wide range of sensors is beneficial in a rehabilitation process, such as electromyography for muscle activity measuring, and inertial measurements units for gait cycle and postural balance measurements (Dobkin, 2013). These sensors are used to measure progress and adjust the rehabilitation process to fit the patient's level, thus improving their user experience. Further on, data collected by those sensors can be visually presented to the patient in VR to enhance the user experience.

2.3 Combining Motion Sensors and Virtual Reality Solutions in Rehabilitation

One of the most reported VR strengths is ecological validity, the degree of similarity of the training to the real world and the potential of the learned skills to be transferred to the patients' everyday lives (Koenig et al., 2019). The authors use an example of making breakfast in a virtual kitchen. A patient prepares food, looks for utensils, makes coffee and toast, listens to the weather forecast, and gets interrupted while doing these tasks by taking phone calls. All of these tasks can be accomplished in VR, both visually and kinesthetically. The kinematic data gathered from the motion sensors, the behavioral data, and log files contribute to a large set of data that can be analyzed for further progress of the patient. Koenig et al. (2019) also highlighted the benefit of adding social interaction. Social interactions can enrich the experience and make the experience more related to the patient's everyday life. Some parts of social interaction involve distractions and disturbances, and patients will need to be prepared for situations like these. Kern et al. (2019) created a VRR program intending to motivate patients to walk for an extended period using a treadmill and VR headset. They created an engaging story with characters where the goal was to rebuild the home of a dog companion through walking. As the patient walks the world rebuilds, visual and auditory cues and small animations enrich the game. The study concluded that gamification elements (i.e., appealing storyline, rewards, and social interaction) increased motivation in gait rehabilitation. The study also reported a higher level of well-being in terms of user satisfaction, anxiety, and simulator sickness than the participants in non-VR conditions.

²<https://www.motekmedical.com/solution/caren>

³<https://www.motekmedical.com>

In a study by Proffitt and Lange (2015), a home-based rehabilitation program was created using a Microsoft Kinect, monitor and PC. The system was tested on four participants, where three out of four found the program usable. The authors concluded that one potential issue with using VR in self-guided rehabilitation programs is that a certain level of technical knowledge is needed to operate the system. Nonetheless, using such technology could be useful in self-guided programs, as the technology seems to increase the amount of fun and motivation. It can also gather data on patient progress, facilitating therapists to tailor rehabilitation programs to specific individual needs.

2.4 Virtual Reality and Neuroplasticity

Neuroplasticity is the brain's ability to change throughout our lives as a result of experience. Neuroplasticity helps us learn new skills, enhance existing capabilities, as well as aid recovery after loss of functionality, i.e. loss of speech, motor control and balance from cognitive impairments. When the brain is damaged, by illness or accidents, the brain has the ability to change and reform neural connections. The brain can reorganize its structure according to the environment (Lawo and Knackfß, 2018). In rehabilitation of impairments related to the brain, such as stroke or Parkinsons disease, therapists try to induce neuroplasticity. For example, a patient suffering from loss of function on one side of the body after a stroke may rearrange or create new neural pathways which were lost with intensive rehabilitation. Rearranging these neurons only happens with the right stimulus and sustainable motivation (Lawo and Knackfß, 2018). Stronger connections in the brain are made by doing the tasks regularly. Rehabilitation starts in the hospital or in a clinic, and usually continues at home after discharge. Lawo and Knackfß (2018) suggest utilizing easy-to-use technology for patients to engage in self-guided programs. In the article they present a set of features and functionalities required for an ideal home solution are presented. One of which is exercises within a personalized, serious-game-based rehabilitation program in a virtual environment. In Table 2, Kleim and Jones (2008) list of principles of experience-dependent plasticity are coupled with VR possibilities suggested by the authors which may facilitate neuroplasticity.

2.5 Cybersickness

The feeling when sitting in a car that is standing still while the car besides starts moving is often a little confusing, nauseous and discomforting. That feeling can occur while using VR as well. There are many terms for this phenomenon. Some call it cybersickness, others call it motion sickness and simulator sickness (LaViola, 2000; Davis et al., 2014). These terms are similar, but with different triggers and some different symptoms. Motion sickness could be triggered by rollercoasters, driving cars and other real-world experiences, and cybersickness (discussed in this work) is triggered by VR. Discomfort, nausea, sweating, fatigue and headache are some of the symptoms of cybersickness (LaViola, 2000). To the best of our knowledge, it is still challenging to define specific characteristics of people whose cybersickness can be triggered by VR. There are three main theories as to why someone gets cybersickness: 1) the Sensory Conflict Theory, 2) the Poison Theory and 3) the Postural Instability Theory (LaViola, 2000). The Sensory Conflict theory is

TABLE 2 | Based on Kleim and Jones (2008): Principles of experience-dependent plasticity further developed to include VR possibilities.

Principle	Description	VR rehabilitation
Use it or lose it	Failure to drive specific brain functions can lead to functional degradation	VR can offer additional, motivating training at home
Use it and improve it	Training that drives a specific brain function can lead to an enhancement of that function	VR rehabilitation facilitates for task-specific individualized and immersive training
Specificity	The nature of the training experience dictates the nature of the plasticity	VR rehabilitation can offer specific experiences
Repetition matters	Induction of plasticity requires sufficient repetition	VR can offer additional, motivating training at home
Intensity matters	Induction of plasticity requires sufficient training intensity	VR rehabilitation can adjust intensity of training. VR rehabilitation coupled with sensors could detect too high or too low training intensity
Time matters	Different forms of plasticity occur at different times during training	Rehabilitation often combines training at a facility and self-guided programs at home
Saliency matters	The training experience must be sufficiently salient to induce plasticity	VR rehabilitation can customize the training environment to facilitate saliency
Age matters	Training-induced plasticity occurs more readily in younger brains	VR rehabilitation allows customization for different age groups
Transference	Plasticity in response to one training experience can enhance the acquisition of similar behaviors	VR rehabilitation facilitates transference
Interference	Plasticity in response to one experience can interfere with the acquisition of other behaviors	VR rehabilitation needs to be developed in collaboration with therapists to minimize the risk of interference

based on the vestibular sense and the visual sense having a conflict with each other, which could trigger motion sickness. This theory is not a feature of VR, and can be triggered in everyday life. For example when movement is seen, but not felt.

Kennedy et al. (1993) created the Simulator Sickness Questionnaire (SSQ), which is the most commonly used questionnaire when investigating motion sickness. It can also be used for cybersickness. The SSQ contains 16 symptoms, scaled from zero (no symptoms) to three (severe symptoms). It is taken two times, once before testing to determine the patient’s health and again right after testing to see if the patient experienced any symptoms.

Different measures can be taken to prevent or at least reduce the risk of triggering cybersickness when using VR. Studies have shown that pleasant music and aroma decrease the risk of cybersickness (Keshavarz and Hecht, 2014; Keshavarz et al., 2015). Research also indicates that having a virtual nose could alleviate cybersickness (Wienrich et al., 2018). Providing a multisensory VR environment, such as including movement, could also reduce the mismatch between the senses. Chang et al. (2020) proposed in their literature review a multimodal fidelity hypothesis, which suggests that minimizing the mismatch

between sensory information could help alleviate cybersickness. In the study by Plouzeau et al. (2015), the level of cybersickness lessened when the participants experienced vibrations corresponding to the visual stimulus in VR. Hardware is another critical factor in preventing cybersickness. Aspects that need to be considered are refresh rate, Field Of View (FOV), screen size, and resolution. Kourtesis et al. (2019) researched different types of technology used in VRR, and their research resulted in a list of suggested technical standards, which is presented in **Table 3**.

The severity of cybersickness varies among users. Factors such as age, gender, emotional and psychological state, health and previous experience with VR can all affect susceptibility to cybersickness (LaViola, 2000; Davis et al., 2014). Some people naturally have a higher degree of cybersickness susceptibility, which might be attributed to the difference in depth perception (Benzeroual and Allison, 2013).

3 A BIOMECHATRONICS LAB FOR REHABILITATION STUDIES

Haptic rendering, associated with virtual/augmented reality, is an emerging term within the field of gaming (Tokuyama et al., 2019), robot control (Liu et al., 2019), training/rehabilitation (Bortone et al., 2018), and human-machine interaction (Sanfilippo et al., 2015; Sanfilippo and Pacchierotti, 2018; Sanfilippo and Pacchierotti, 2020). Haptic rendering is the process of computing and generating forces in response to user interactions with virtual objects (Salisbury et al., 1995).

TABLE 3 | Suggested technical standards of VR in rehabilitation.

Feature	Suggested standard
Display screen	Good quality (OLED or upgraded LCD)
Display resolution	Minimum 960 × 1,080 sub-pixels per eye
Refresh rate	No less than 75 hz
Field of view	No less than 110 degrees

Concerning physiotherapy, haptic rendering has been showing indications of enhancing learning progression and user experience in people with reduced motor skills due to stroke (Yeh et al., 2017; Pareek et al., 2018). With that being said, haptic rendering is still a relatively new term in the context of physiotherapy and needs further researching to be properly exploited.

Lack of the sensation of physical interaction is the main factor differentiating a virtual world from the real world and the gap between those worlds limits the use of an artificial environment in areas other than gaming. It is of interest to couple the two worlds by reproducing virtual, dynamic interactions mechanically, thus reducing the gap between the artificial world and the real world. Since it is all about recreating forces to mimic interactions within the virtual world, haptic rendering can be thought of as a gateway between the virtual world and the physical world. The physiotherapeutic benefits of immersing a person in a virtual world by the aid of haptic rendering are, among others, physical engagement of patients, keeping the training on a stationary rig for optimal monitoring and assessment, the possibility to create controlled, user-specific exercises and difficulties, and to include objectives and rewards in the training routines. However, including haptic rendering in physiotherapy also poses challenges. The physical structures of the mechanical setups can feel intimidating, depending on the size and complexity of the machine. Moreover, people in need of rehabilitation often have mobility problems, which highly affects the physical design and operation criteria of the machine. Also, there is always a safety concern in situations where a machine is in direct collaboration with a human, especially in cases where the purpose of the machine is to act a force on the human. A robot should not be able to harm any human, which means many considerations must be made when designing and developing a haptic render-based rehabilitation system for physiotherapists and home-use. These considerations, along with ethical problems and cost-over-function, are all factors contributing to limiting its current occurrences as tools used by health experts. This limitation of usage affects research on the topic and impairs the advancement within the field. To contribute to the study of using haptic rendering for rehabilitation and training, a proof-of-concept haptic rendering system was developed for the purpose of enabling lower limb assessment, training and rehabilitation in cooperation with an interactive, virtual world (Jomås and Lien, 2020).

3.1 Mechanical Setup

To model the physical rendering of a dynamic environment, we used a 6 DOF Stewart platform (Dasgupta and Mruthyunjaya, 2000) employed at the Norwegian Motion Laboratory at the University of Agder (UIA). The Stewart platform is a Rexroth eMotion 1,500, which is specifically designed for simulation purposes.⁴ A treadmill is mounted on top of the motion

platform to study locomotion performance in patients with complications concerning lower limb movements. The treadmill is equipped with embedded load sensors to measure load location and magnitude. The selected sensors enable measurements similar to the ones that can be collected with clinical force plates. The possibility of performing such measurements is important for the assessment of biomechanical motion and balance (Mansfield and Inness, 2015), and to enable the patient to directly influence the motion of the platform. The treadmill is also equipped with an industrial drive inverter to attain full control over the treadmill belt's velocity, contributing to personalize rehabilitation programs. Moreover, a state-of-the-art motion tracking system from Qualisys is mounted on the ceiling above the motion platform to provide real-time visual monitoring of the skeletal structure during dynamic exercises.⁵ The selected camera system enables researchers and practitioners to conduct diagnosis and real-time assessment of the rehabilitation process. A safety harness frame with railings encapsulates the treadmill which is designed to support the patients during operation and to catch them as soon as possible in case of a fall, preventing them from falling onto the treadmill or off the rig. In addition, an emergency stop is made easily available for both the practitioner and patient. Strict safety assurance and measures, as well as emerging standards in this area, need to be considered given that the system comprises human-machine collaboration. A visual description of the components comprised by the biomechanics lab can be seen in **Figure 1**.

3.2 Dynamic Model of Surface Interaction

To enhance the immersive feeling of virtual reality, a dynamic model of surface interaction is implemented into the platform's control flow. The purpose of the dynamic model is to mimic the response of a surface when "physically" interacted with in the virtual world. The dynamic response of the model can be adjusted to represent specific balancing scenarios such as snowboarding, skateboarding, surfing, and also walking scenarios such as walking on an air mattress, on soft grass or on concrete. Depending on the patient's location and pressure magnitude on the treadmill, the model will provide the Stewart platform with commands to make it simulate the interaction between the patient and the corresponding virtual surface. This setup enables the eligible practitioner/operator to fully control the platform's motion or to include patient intervention by passing control signals through the model. This makes the setup a suitable environment for assessment and rehabilitation where specific and personalized movements can be generated. The control architecture and interaction-model are developed in LabVIEW - a software that offers a graphical programming approach.⁶ The LabVIEW program is deployed onto a MyRIO student embedded device, which supports both LabVIEW graphical code or C.⁷

⁴<https://www.boschrexroth.com/en/xc/industries/machinery-applications-and-engineering/motion-simulation-technology/products-and-solutions/6dof-motion-platform/emotion-1500/index>

⁵<https://www.qualisys.com/cameras/5-6-7/>

⁶<https://www.ni.com/en-no/shop/labview.html>

⁷<https://www.ni.com/en-no/shop/hardware/products/myrio-student-embedded-device.html>

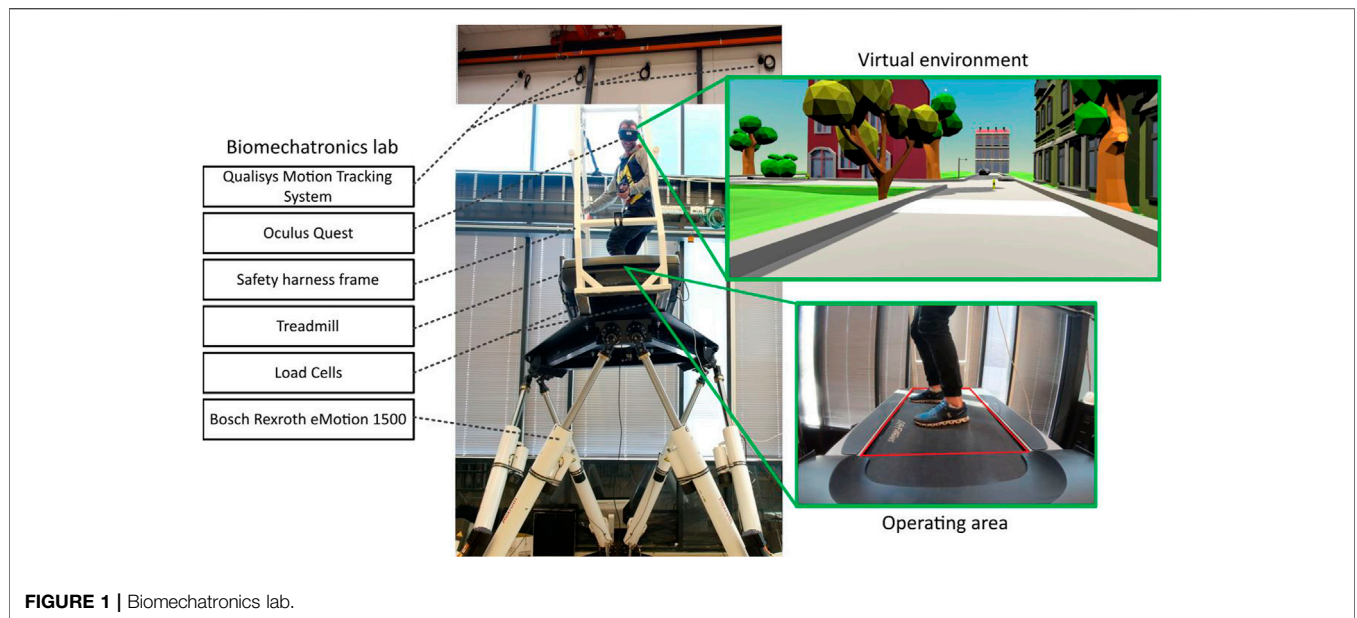


FIGURE 1 | Biomechanics lab.

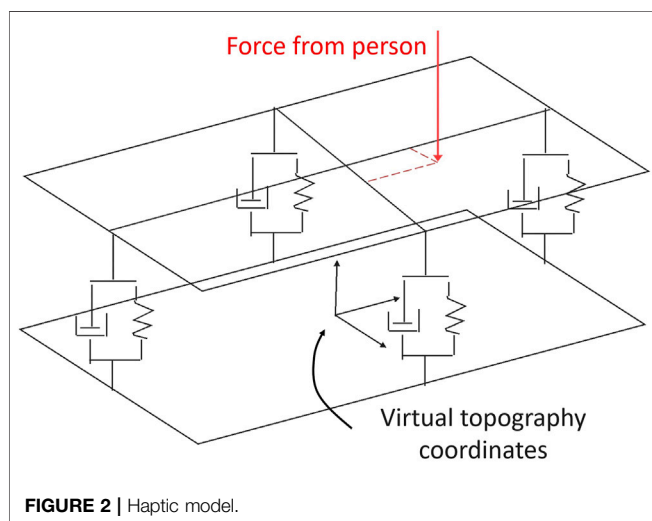


FIGURE 2 | Haptic model.

Although LabVIEW is ideal for quick-paced proof-of-concept programming, the architecture quickly becomes indecipherable for larger programs containing multiple statements and loops. Therefore, more traditional text-based programming languages might be preferable to use at a later stage.

The haptic model utilizes input data from four load cells one mounted in each corner of the treadmill, and also the coordinates of the topography of the virtual surface at the feet of the virtual, first person character within the virtual world. Based on trigonometry, the location and magnitude of the weight applied by the person on the treadmill are estimated. The haptic model consists of four mass-spring-damper submodels interconnected by two rectangular surfaces within a three-dimensional space, as illustrated in **Figure 2**.

The haptic model, also referred to as board model, is developed by using State-Space architecture in LabVIEW. As

shown in **Figure 2**, the location and magnitude of the weight applied by the user act on the upper surface while the lower surface is mimicking the virtual topography. Then, the coordinates of the upper surface (the board) are transmitted to the Stewart platform for physical rendering of the virtual board's motion. Each mass-spring-damper model can be individually modified thus enabling the possibility to render multiple different surface properties depending on the desired scenario. For the test run, the tilt angle of the board model relative to absolute coordinates determined the virtual turn rate, much like riding a snowboard in powdery snow. The information flow between the different components within the system, including the data processing unit containing the haptic model, is shown in **Figure 3**. The data processing unit processes information from sensors and the virtual world, couples them through the haptic model and provides the user with a haptic-audio-visual experience by actuating the platform, generating sound and displaying a virtual scenario correspondingly.

3.3 Virtual Reality Environment and Implementation

Unity is a real-time professional 3D development platform with built-in IDE.⁸ In this project, it is used to generate and render a virtual world, and to provide information about the topography necessary for the Stewart platform to mimic the surface pose in the real world. The Unity VR application and the LabVIEW program exchange information via a middleware gateway realized in Python. The topography information, along with the patient's intervention through the haptic interface, is then handled by the controller to provide a set of coordinates for the

⁸<https://unity.com/>

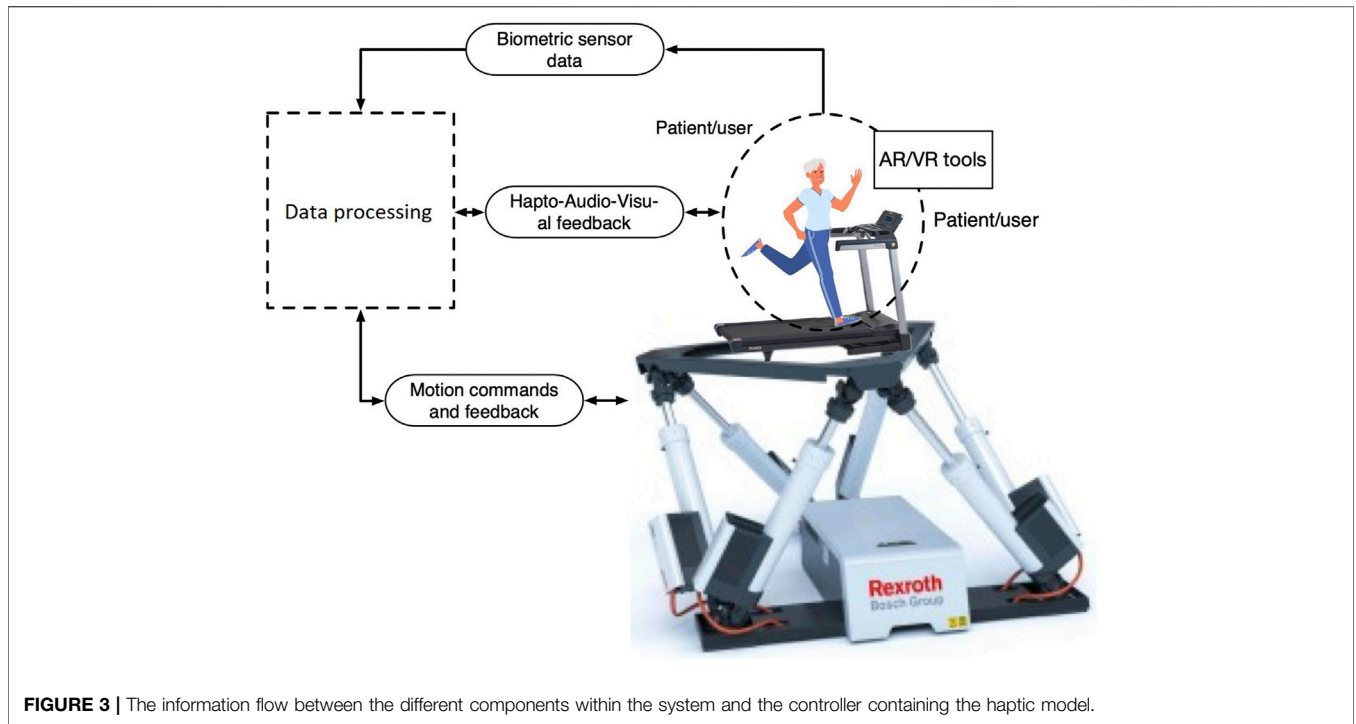


FIGURE 3 | The information flow between the different components within the system and the controller containing the haptic model.

TABLE 4 | Therapeutic aim and game design choices.

Therapeutic aim	Game design choices
Postural control, balance, weight bearing Standing balance, asymmetric weight distribution, impaired weight shifting Trunk control on unstable surface, gait abnormality	Leaning to navigate over speed bumps to collect stars Weight transfer from left to right leg to balance the platform Leaning to navigate over uneven surface to collect stars on motion platform

Stewart platform’s pose. This is a continuous, real-time process that generates an immersive fidelity of the virtual world.

The VR environment consists of a small city with an intersection. Along the road, there are different obstacles like speed bumps, slopes, rocks and other bumps that the patient has to overcome to obtain all the stars that are scattered along the road. The gameplay is simple, collect all the stars and try to maintain your balance. To collect a star the patient has to navigate the character in the scenario directly into the star, which, when caught, triggers a distinct audio to indicate that the star is indeed captured. To test the balance of the patients, the possibility of cybersickness and the biomechatronic lab’s functionality, the stars are strategically placed along the road. For example one of the stars is placed at a dead end so that the patient had to turn 180 degrees to go back and try another path, while other stars were placed on the slopes and bumps so the patient had to navigate over them. Currently, there are no points calculation or time measurements in the scenario, but in the future, these aspects could be added. The initial plan was that the users would walk on the treadmill and lean to either side to turn. This could not be implemented because of restrictions that prevented access to the biomechatronics lab facilities. Instead, the biomechatronics lab operator manually sets a speed to the character in VR and the user can navigate

and turn by leaning, similar to skateboarding. The VR scenario of skateboarding was discussed with therapists before development (Madshaven and Markseth, 2020) and consideration was given to related previous work involving patients (Liao et al., 2018). In **Table 4** the therapeutic aim and the game design choices are displayed. A part of the rehabilitation of stroke patients is focused on sensory stimuli and shifting weight on the legs from side to side. In discussion with the therapists, patients at their facility sometimes use a Nintendo Wii Balance Board (WBB) with Wii Fit in weight-bearing and balance training. For now, such training is minimal and only for fun because, according to the therapists, the patients tend to have a higher focus on winning the game rather than performing the movements correctly. This may have a negative impact on the therapeutic progression and could set back the progression obtained through traditional rehabilitation. Designing rehabilitation games to force the patient to do the right movement to “win” could make the use of such systems more suited. The scenario was developed to be used with the biomechatronics lab and the home version.

In **Table 5**, three different VR headsets which were available at our facilities at the time are presented with their specifications. Although the HTC Vive fulfilled most of the suggested standards, the headset utilized for the biomechatronics lab was the Oculus

TABLE 5 | Comparison of features on Oculus Quest⁹, Oculus Rift^{10,11} and HTC Vive (Borrego et al., 2018).

Feature	Oculus Quest	Oculus Rift	HTC Vive
Display resolution	3200 × 1440 OLED	2160 × 1200 OLED	2160 × 1200 OLED
Refresh rate	72 Hz	90 Hz	90 Hz
Field of view (degrees)	Hor: 94 vert: 93	110 ^a	Hor: 110 vert: 113
Requires external sensors	No	Yes	Yes
Requires external computer	No	Yes	Yes
Can be used with glasses?	Yes	Yes	Yes

^aCannot find vertical FOV

Quest. The reasoning behind this is that the Quest offered the best technical solution. It has internal sensors and it could be operated with a single USB-C type cable. The motion platform moves up and down approximately 1 m during operation, making accurate motion tracking challenging when using headsets that requires external sensors to function. The Oculus Quest is a standalone VR headset, it is wireless and does not require a computer to function. The HTC Vive can also function wirelessly. A wireless adapter can be purchased, but you still need a computer for the HTC Vive to function and external sensors for tracking, making it less portable than the Quest.

3.4 System Design Evaluation

The current biomechatronics lab was developed as a proof-of-concept to test the possibility and performance in terms of fidelity and immersiveness of combining VR and a physical motion platform. Even though the physical components used and how their assembly resulted in an unnecessarily over-dimensioned rig with limitations concerning usability and dynamic response, the tests indicated promising results regarding the increase of fidelity and immersiveness. Once engaged in the virtual world augmented by a sensible physical response, the mind quickly adopted artificial physics, and orientation felt increasingly natural and instinctive. The setup proves its use as a proof-of-concept platform for biomechanic motion assessment and training/rehabilitation, and will be used for further research within this field. In the future however, the development of a more compact and responsive solution to the mechanical system is desired to increase the ease of initiating assessment/rehabilitation and operation, but also to enhance the motion rendering.

4 A SIMPLIFIED HOME VERSION FOR PORTABILITY

A prototype of a simplified home version of the biomechatronics lab was created to explore the possibility of a portable

⁹Martindale, J. (2020). Oculus Quest vs. Oculus Rift. Library Catalog, <https://www.digitaltrends.com/virtual-reality/oculus-quest-vs-oculus-rift/>.

¹⁰Binstock, A. (2015). Powering the Rift, <https://www.oculus.com/blog/poweringthe-rift/>.

¹¹Orland, K. (2016). The Ars review: Oculus Rift expands PC gaming past the monitors edge, <https://arstechnica.com/gaming/2016/03/the-ars-review-oculus-rift-expandspc-gaming-past-the-monitors-edge/>.

rehabilitation system. Many people in Norway live in areas without a rehabilitation facility. Sometimes patients have to travel far to receive professional help. Therapists also supplement the rehabilitation with self-guided programs at home. Furthermore, because of COVID-19, patients had to rely more on in-home self-guided programs. Even though a home version has limitations on the movement dimension, it presents an affordable and portable solution that could be used in self-guided rehabilitation programs.

The home version consists of a WBB, Oculus Rift VR headset and a PC. The WBB is used for navigating the character in the VR environment. To do this the user has to lean forward, backward or to the sides. The same way as in the biomechatronics lab. There are four pressure sensors located inside the WBB that measure the user's center of pressure (Clark et al., 2010). By shifting weight on the board, the WBB can be utilized as a game controller by converting the output data into keystrokes. An open-source program called the WiiBalanceWalker¹² was used to handle this. The program connects the WBB through Bluetooth, and generates keypresses translating to the keys W, S, D and A or the keys up, down, left and right.

Figure 4 shows the portable home version. For this prototype, the plan was to use an Oculus Quest wirelessly connected to a WBB. However, it was not possible to connect the WBB directly to the Oculus Quest via Bluetooth. Hence a personal computer (PC) was considered to first connect the WBB, then connect a VR headset. At the time for user testing, the Quest was very limited in terms of which USB-C cables would work, so an Oculus Rift was used instead. Since then, the Oculus Quest had a new update that allows for connection using most types of USB-C cables. The VR environment is the same as used in the biomechatronics lab.

5 USER TESTING

5.1 Aims of the User Tests

The biomechatronics lab's observational testing aimed at getting initial feedback on the system's functionality and user experience. The user testing aims to test the home-based rehabilitation system's usability, evaluate the user experience, and to see if this system could be used at home, outside of rehabilitation facilities.

¹²<https://github.com/lshachar/WiiBalanceWalker/releases/tag/v0.4>



FIGURE 4 | Home-based system.

5.2 Biomechanics Lab

Due to Covid-19 and related university guidelines, the number of people and time allowed in the Motion Lab was restricted. This meant that we could not conduct user testing with external participants in the biomechanics lab. Our time-slot for lab access had to accommodate for both the final system integration and an observational test. We tested on five people, three of them related to the project. All participants were men between the age of 25 and 40, three of them had minor previous experience with VR.

The methods used were direct observation in a controlled environment, followed by oral feedback. The participants voiced their thoughts about the user experience and the functionality of the system.

All participants were in the same room, at all times during user testing. One by one, the participants mounted the biomechanics lab and got secured to the safety frame with a harness. When they were ready and comfortable, they were asked to collect six stars around the VR environment. During the test, the participants were encouraged to continuously express their thoughts about the experience, following the Think Aloud protocol.

The results from user testing of the biomechanics lab show that the user experience was enjoyable and fun. None of the participants experienced any cybersickness. One participant said that he felt a little disoriented when looking down in the VR environment because he couldn't see any legs. One of the participants was so immersed that he forgot how high up the motion platform was. Combining the biomechanics lab with the VR system proved successful and the systems functioned together with no perceived delays.

5.3 Home-Based System

Five people participated in user testing, four men and one woman. The participants' ages ranged from 30 to 50 years. Four of the participants reported that they had used VR before and had some experience with video games. All of the participants were technologically competent. Although this was a



FIGURE 5 | Structure of the user test conducted with the home-based system.

TABLE 6 | Results from the simulator sickness questionnaire.

Question	Pre					Post				
	P1	P2	P3	P4	P5	P1	P2	P3	P4	P5
General discomfort	0	0	0	0	0	0	1	1	0	0
Fatigue	0	0	0	0	1	0	0	0	0	1
Headache	0	0	0	0	0	0	1	0	0	0
Eyestrain	0	0	0	0	1	0	1	1	0	1
Difficulty focusing	0	0	0	0	0	0	1	0	0	0
Increased salivation	0	0	0	0	1	0	0	0	0	0
Sweating	0	0	0	0	1	0	0	1	0	1
Nausea	0	0	0	0	0	0	1	1	0	0
Difficulty concentrating	0	0	0	0	1	0	1	0	0	1
Fullness of head	0	0	0	0	0	0	1	0	0	0
Blurred vision	0	0	0	0	1	0	0	0	0	0
Dizziness (eyes open)	0	0	0	0	0	0	0	0	0	0
Dizziness (eyes closed)	0	0	0	0	0	0	1	0	0	0
Vertigo ^a	0	0	0	0	0	0	0	0	0	0
Stomach awareness ^b	0	0	0	0	2	0	0	0	0	2
Burping	0	0	0	0	0	0	0	0	0	0

^aVertigo is experienced as loss of orientation with respect to vertical upright.

^bStomach awareness is usually used to indicate a feeling of discomfort that is just short of nausea.

small sample size, a small number is often enough for assessment in usability studies (Lazar et al., 2017), which focus on finding potential usability problems. Two semi-structured interviews with closed-ended and open-ended questions were created to get information about the participants, what they thought about the VR solution, and to better understand the VR solution’s user experience and usability. The Simulator Sickness Questionnaire (SSQ) was administered to measure cybersickness symptoms. During the user test, notes were taken on how the participants were doing and what was said during testing.

Figure 5 shows the structure of the user tests. The test participants were brought into the test area and informed of the test’s procedure and their rights as participants. After the first

interview and SSQ, the participants were instructed on using the equipment and had a test run. When the participants felt comfortable with the equipment and how to use it, they collected six stars along a test-track in the VR environment. During the test, participants’ activities were observed and the duration of given user tasks was recorded. After the test, the participants answered again the SSQ and responded to post-interview questions.

The findings from the participants’ post-interviews indicate that the participants found the home-based system easy to learn how to use, effective and efficient to use (in terms of technical usability). One of the participants remarked that catching the stars was easy but the path was difficult to navigate. Two of the participants found the system to be slightly frustrating with regards to the sensitivity of the WBB. All but one participant felt safe when testing the system, where one participant remarked that he would feel safer with nearby support in case of imbalance. Three out of five participants experienced no discomfort or symptoms of cybersickness during testing. The results from the SSQ (Table 6 and Figure 6) revealed that two of the participants experienced mild symptoms of cybersickness. The two youngest participants, between the age of 30 and 35, experienced mild dizziness, headache, eyestrain, and nausea. All the participants remarked having fun during testing.

5.4 Discussion

Given the small sample size in user testing, this work can not generalize the results pertaining to the incidences of cybersickness while using the developed systems. The Sensory Conflict Theory might explain why the biomechatronics lab did not induce any symptoms. In the biomechatronics lab, the motion platform moves with the environment seen in the VR headset, which could reduce the risk of triggering cybersickness (Chang et al., 2020). One of the participants mentioned that adding legs to the character

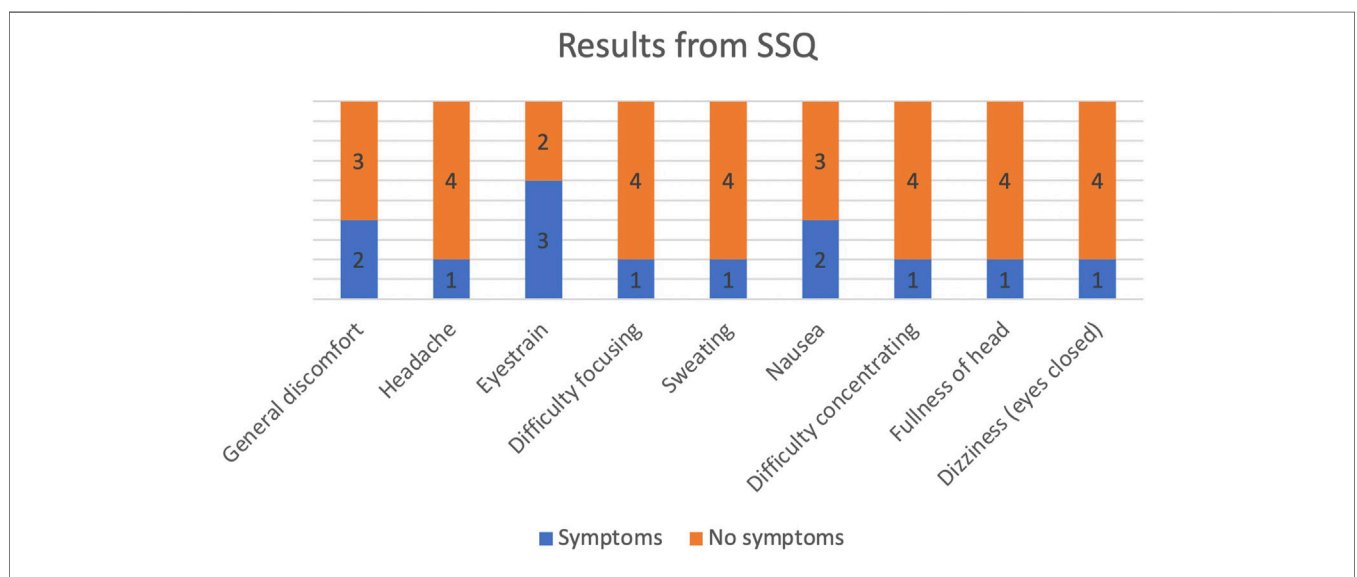


FIGURE 6 | Representation of SSQ results from Table 6: This shows how many participants experienced mild symptoms (Score of 1 or 2 in SSQ) of cybersickness.

could improve the system, thereof improving the user experience. When looking down in VR, it can be somewhat disorienting not seeing one's legs. None of the participants involved in testing the home-based system mentioned this. The level of realism in the biomechatronics lab is higher than in the home-based system because of the added sense of movement. Providing more sensory information could make users expect a higher level of realism because of the increased immersion in the experience. Users can perform various rehabilitation tasks in a more realistic setting, with varying levels of difficulty in the biomechatronics lab. Given the possibilities to create varying challenges in the VR environments, it would be possible to make adjustments according to individual users' responses, hence sustaining their engagement, motivation and a sense of control. Users familiar with sports and training facilities are likely to find it natural to use the biomechatronics lab, hence increasing the quality of overall experience and user satisfaction.

User testing results indicated that the home system might induce cybersickness in some individuals, and the WBB should be more responsive. Furtheron, the WBB does not add the sense of movement, which might be the reason why the home system-induced more symptoms of cybersickness than the biomechatronics lab. The WBB was calibrated to each individual. Moving ones feet from the calibrated area could contribute to the lack of sensitivity experienced by some of the participants. Potential patients may need to calibrate the WBB themselves for home-based rehabilitation which may lead to low sensitivity and accuracy.

As Bonnechre et al. (2015) suggested, there is a high correlation between using laboratory force plates and WBB in balance assessment. Although the WBB presents a viable low-cost portable solution to laboratory force plates, our user tests suggest that some users may find it difficult to use as a game controller. Based on our results in testing the home-based system, we suggest using new and improved hardware in terms of balance boards.

6 CONCLUSION

Two virtual reality supported rehabilitation solutions were developed and user-tested. One was a biomechatronics lab consisting of a 6 degrees of freedom motion platform, a treadmill with embedded load sensors for load location and magnitude, a motion tracking system, and virtual reality system for interaction in a virtual environment (**Supplementary Video 1**). The other solution was a home-based system consisting of a Nintendo Wii Balance Board with pressure sensors for balance assessment and navigation in 3D with an Oculus Rift. Both solutions, developed as proof-of-concept prototypes, were tested with a small number of users using observations, the Simulator Sickness Questionnaire, pre and post-test interviews. The user test results indicate that the home-based system would benefit from using a balance board with better sensitivity and that the system induced cybersickness in some test persons. User testing of the biomechatronics lab indicates that the embedded load sensors in the treadmill offered a better user experience because it was more sensitive and easier to operate. None of the participants in user testing of the biomechatronics

lab experienced cybersickness. Although the participants were similar but not identical, we hypothesize that reason is that the biomechatronics lab reduces the mismatch between the visual and vestibular sense, as proposed in the Sensory Conflict theory (LaViola, 2000). Overall, the findings indicate that the proposed solutions are technically feasible, but further testing with patients and rehabilitation experts is needed to determine if this is transferable to future patients.

6.1 Proposed Future Work and Planned Activities

Developing a more affordable, simpler to use, compact, and overall, more comprehensible version of the current proof-of-concept biomechatronics lab is crucial in order to enable local stakeholders within the health sector to obtain and use the technology at their facilities. Moreover, home-based haptic device alternatives, consisting of just enough features to target the specific user groups instead of an all-round rig, may have a huge impact on the general progression in-home rehabilitation and training and should be looked further into. In the future, the biomechatronics lab will hopefully not only be used for rehabilitation of balance and gait problems in patients with cognitive impairment, but for physical therapy generally.

In future research, the systems should be tested on a larger sample size of healthy test participants before testing on patients. Before patient testing, the systems must be developed for safe testing. For the biomechatronics lab, adding sensors such as EMGs and ECGs could improve rehabilitation and give therapists valuable information about the patient.

New and improved hardware in terms of VR headsets and balance boards should be considered to increase usability and possibly reduce cybersickness. Oculus has released a new version of the Quest, called Oculus Quest 2. The Oculus Quest two is lighter, which causes less strain to the neck and head. It also has an improved refresh rate at 90 hz as well as improved resolution.¹³ Reconfiguring the Oculus Quest to function wirelessly in both the biomechatronics lab and home-based system would remove the need to have a PC, which is more cost-effective and convenient. The WBB is considered outdated, and could not connect via Bluetooth directly to the Quest. Improved hardware in terms of balance boards was not easily available, but there are some alternatives such as Sensamove's Sensbalance MiniBoard¹⁴ which could be tested. Recent developments of portable motion platform rigs show promise for a home-based system.¹⁵ A further step towards a home-based solution would require studying remote assistance and observation solutions by rehabilitation experts.

The current VR scenario should be further developed, and additional scenarios should be created. Adding motivational elements, such as getting points, being timed and more engaging storylines, the overall VR experience could be improved. Adding sounds, music and interactions would make the experience even more immersive. The new scenarios should be developed in collaboration with both therapists and patients.

¹³<https://www.oculus.com/compare/>

¹⁴<https://www.sensamove.com/en/sensbalance-miniboard/>

¹⁵<https://www.gforcefactory.com/edge-6d>

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: <https://gitlab.com/juliemad91/vr-rehabilitation> <https://uia.brage.unit.no/uia-xmlui/handle/11250/2682565> <https://uia.brage.unit.no/uia-xmlui/handle/11250/2680815>

AUTHOR CONTRIBUTIONS

JM and TM developed the theory concerning VR and rehabilitation and created the VR experience for the rehabilitation systems, designed and carried out the user testing under the supervision of FR and GI. MO and DJ created the theory for the biomechanics lab at Top Research Centre Mechatronics, University of Agder (UiA). DJ contributed in the assemble of the physical proof-of-concept rig located at the lab under supervision of MO. The VR experience at the biomechanics lab, comprised by visual and haptic rendering, was a result of collaboration between JM, TM, and DJ. JM, TM, and DJ wrote the manuscript with the support of FR, GI, and FS. MO conceived the original idea. FS contributed to the design of the work. FS, FR, and GI was involved in drafting the work and revising it critically. FS, FR, and GI has approved the version of the manuscript to be published. The project was supervised by FR, GI, FS, and MO.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/frvir.2021.645042/full#supplementary-material>

Supplementary video 1 | The Biomechanics Lab at the University of Agder.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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