A Virtual Reality Rehabilitation Interface with Augmented Sensing, Interaction, and Visualization Techniques

by

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ABSTRACT

With the advanced development of multimodal sensing and rendering technologies, Virtual Reality (VR) has attracted enormous interest in unsupervised physical rehabilitation owing to its decisive advantages in turning traditional physical touchpoints into digital simulated empathy machinery. The shift from treatment rooms to the VR realm allows the scarce resource of rehabilitation services to reach a wider population. While traditional physical space designed the external environment, the virtual display satisfied users with self-awareness through virtual avatars and multisensory feedback. Thus, extensive research investigated innovative sensory input techniques, particularly motion tracking and mapping.

In response to this reverted design methodology, the primary object of this thesis is to survey an effective design and engineering paradigm of virtual rehabilitation spaces, including sensing technologies, interaction methods, and augmented feedback. The paper investigated a VR rehabilitation simulator that integrated muscle engagement sensing inputs, conventional motion simulation, and immersive VR displays. It is a three-in-one system consisting of two-dimensional input systems, a high-precision, low-latency optical motion capture system, a wearable Electrical Impedance Tomography (EIT) device, and an output system, a virtual rehabilitation environment that allows real-time visualization and interaction of muscle engagement and motion feedback. To validate the functionality and efficiency of this system, two user research were conducted. Study 1 evaluated how the enhanced system helped participants improve therapeutic exercise completion accuracy, while study 2 measured how the system empowered remote physical therapist evaluation quality without the in-clinic diagnosis. The results showed that muscle engagement visualization substantially improved the accuracy of therapeutic exercise (~15%) and facilitated the therapist's remote assessment quality. Finally, the paper discussed a range of alternative low-cost technologies, the future implication of the VR program as an at-home rehabilitation training tool, and more research directions.

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PUBLICATIONS

This thesis contributed the VR development and User Research to the following publication currently under submission:

Junyi Zhu, Yuxuan Lei, Aashini Shah, Gila R. Schein, Hamid Ghaednia, Joseph H. Schwab, Casper Harteveld and Stefanie Mueller. 2022. MuscleVR: Improving Unsupervised Physical Rehabilitation by Monitoring and Visualizing Muscle Engagement. In Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology (UIST ’22). ACM.

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1 Overview

1.1 Introduction

As early as 1930, *Stanley G. Weinbaum* demonstrated his vision of Virtual Reality (VR), the non-traditional interactive interface, as immersive empathic magic in the science fiction novel, *Pygmalion's Spectacles* [1]. With the increasing maturity of multimodal sensors, motion tracking, and rendering technologies, VR devices have equipped with simulation capabilities to emulate the physical world and means of interaction to manipulate virtual events. Specifically, the accurate mapping of physical entities to digital counterparts became feasible and accessible. Researchers in multiple fields, such as game, education, exhibition, and medical fields, explored how this revolutionary hybrid paradigm will redefine cognition and extend the boundaries of interaction. In particular, in the medical field, VR-supported unsupervised physical rehabilitation systems have received extensive attention in the past decades.

Physical rehabilitation is a series of chronic medical interventions committed to alleviating musculoskeletal dysfunction and improving physical performance to a healthy level. When people receive rehabilitation services, healthcare providers deploy the environment, assistive devices, and physical therapist resources appropriate to the needs of the medical condition and treatment plan. According to the *World Health Organization (WHO)*, approximately 2.4 billion people worldwide benefit from this type of care [2]. This demand continued to rise as population longevity increased and the distribution of chronic diseases and disabilities accelerated. However, traditional rehabilitation models have long faced several challenges such as therapist shortage, centralized distribution, and constructional and operational costs [3]. Therefore, researchers proposed the concept of VR rehabilitation space. They believed that the unique medium could replace the constrained physical situation with a highly customized simulated environment to meet several decisive requirements for rehabilitation interventions, such as daily treatment [4], task-oriented training [5], and momentum activation [6].

Most VR research related to unsupervised physical rehabilitation focused on developing innovative sensing input techniques, especially motion tracking. To achieve high-precision, low-latency motion tracking, researchers have explored three major technical approaches: vision-based [7], force-based [8], and inertial-based [9]. While motion monitoring technologies brought a valid assessment dimension to rehabilitation, they cannot substitute for the therapist's expertise in interpretability and evaluation accuracy. In addition, motion data is limited as to what information they can provide to the therapist because different groups of muscles may drive identical movements. Monitoring and analyzing muscle group engagement is a critical metric for maintaining the quality of unsupervised rehabilitation assessments [10]. Traditional physical rehabilitation uses motion tracking to determine the quality of exercise execution, but post-rehabilitation assessments are generally based on muscle engagement. However, muscular contraction and stretching behaviors are often too subtle to be perceived. Given the vital relevance of muscle to physical rehabilitation, the inclusion of muscle engagement visualization in VR displays is warranted. Yet, few researchers have incorporated this information into VR visualization settings. Moreover, existing VR rehabilitation research also lacks reflection beyond sensing technologies.

The unsupervised physical rehabilitation VR space needs to systematically reconsider its design and engineering paradigms (including sensing technologies, interaction methods, and augmented feedback) to remain relevant and efficient in new service models. This paper hypothesized that designing a virtual experience with enhanced sensing techniques, interaction methods, and VR display interfaces will set up an effective paradigm to improve unsupervised physical rehabilitation.

Therefore, this paper developed a VR rehabilitation simulator that incorporates motion simulation and muscle engagement visualization. It is a three-in-one system consisting of two input systems, a high-precision, low-latency optical motion capture system and a wearable Electrical Impedance Tomography (EIT) device for thigh muscle monitoring, and an output system, a virtual rehabilitation interface that visualizes motor feedback and muscle engagement in real-time. In the VR interface, users are presented with a training regimen panel, a standard exercise reference panel of a physical therapist, a streaming patient avatar driven by motion and muscle engagement data, a muscle visualization panel, a text-voice exercise instruction panel, and a simulated environment carrier.

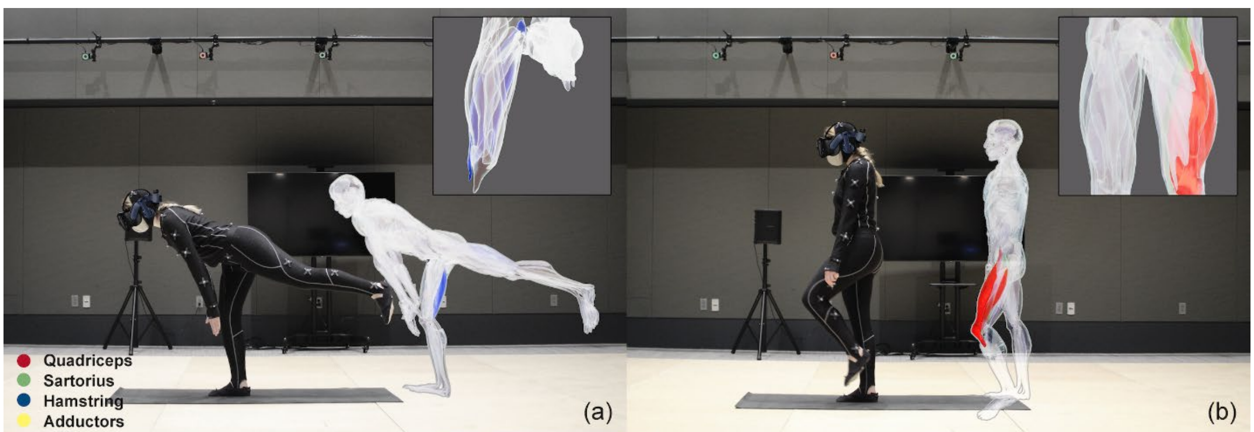

Figure 1 VR Rehabilitation Simulator in Use

Then, the VR rehabilitation simulator was put into practice to validate the overall usability and capability. This paper implemented two user studies. In Study 1, 10 participants performed lower extremity exercises with a VR rehabilitation simulator supported by augmented motion and muscle engagement feedback compared to a traditional motion-only VR system. This user research evaluated how the enhanced system helps participants improved therapeutic exercise completion accuracy. Afterward, Study 2 measured how the enhanced system empowered remote physical therapist evaluation quality without an in-clinic diagnosis. The results showed that the VR rehabilitation simulator with augmented multidimensional visualization substantially improved the accuracy of therapeutic exercise (~15%) and facilitated the quality of remote assessment. Finally, the paper discussed a range of alternative low-cost technologies, the future implication of the VR program as an at-home rehabilitation training tool, and more research directions.

1.2 Motivation

1.2.1 In response to the Pandemic

The outbreak of Coronavirus disease has made physical-level exposure a public health burden, leading to an accelerated shift of many activities to the virtual realm. Rehabilitation is among the health services most affected by the pandemic. In many countries, more than 50 percent of people faced a shortage of rehabilitation resources and sought remote help [2]. According to *McKinsey & Company*, about 61% of Americans have made virtual care appointments since March 2020, which is 38 times higher than pre-covid and is expected to grow at 38 percent over the next five years [11]. Therefore, this paper considers how new technologies and design paradigms can be adopted to accommodate changes in the remote healthcare model during the special periods.

1.2.2 Formulative Study

Prior to this research, *MIT CSAIL Human Computer Interaction Engineering Group (HCIE)* conducted a formative study to understand the overall challenges and current requirements in unsupervised physical rehabilitation [12]. Researchers conducted one-to-one semi-structured interviews with seven physical therapists including four males and three females aged 27-35 (M=30.8, SD=2.99). The interviews gathered information about challenges that the physical therapists encountered and valid input evidence that they would like to acquire during the telerehabilitation assessment process. Multiple physical therapists provided recurring perspectives, suggesting: (1) Remote diagnosis of patient conditions often relies on self-reports (e.g., *KOOS* (Knee Injury and Osteoarthritis Score) [13] and *LEFS* (Lower Extremity Function Scale) [14]), but the information provides limited insight. (2) Patients are always required more in-clinic therapeutic training before the unsupervised execution of new and more complex exercises. (3) Real-time sensing devices can be highly instrumental in accelerating the synchronization of information between patient and therapist and providing more high-quality feedback. Specifically, several therapists expressed the need for real-time training process recording and augmented physiological data feedback, especially muscle and joint activity.

Most of the difficulties identified in this study are caused by limited knowledge and awareness of exercise execution. These problems can be solved by a rehabilitation simulator combining high-quality, low-latency sensor inputs and interactive virtual interface outputs.

1.2.3 Benefits of VR

Compared with traditional screen-based interface and operation, Virtual Reality (VR) technology is characterized by the "3I", i.e., immersion, interaction, and imagination [15]. The virtual display delivers an immersive sensory experience, real-time responsive interaction methods, and customized and narrative events to users by creating a multimodal computer simulation system. It brought new applications to multiple telemedical fields, such as medical imaging [16], rehabilitation [17], and telesurgery [18]. Over 5,000 studies are dedicated to combining and communicating VR with sensor technologies to record and measure multiple forms of physiological behavioral responses for more accurate clinical assessment and control [19]. More studies acknowledged the capability of VR to increase treatment adherence and compliance and reduce patient fatigue and anxiety from repetitive exercise. Based on the research of related work, the following lists the advantages of why the thesis uses VR as a primary carrier.

(1) **Augmented Feedback:** In VR, patients remain in sync with the treatment plan, real-time anthropometric feedback, and algorithm-based assessments during unsupervised physical rehabilitation. They can interact purposefully, rehearse, rectify incorrect exercise postures, and transfer muscle memory and skills to the real world. In the long term, patients gain positive mental cues with ongoing recognition of the steady improvement of their condition in therapeutic exercises.

(2) **Immersive environments:** VR is an essential device for providing a sense of presence and immersion. It can break the limits of territory and places by delivering a compelling simulated spatial experience for patients who have difficulty traveling due to injury or illness. Immersive therapy reproduces custom scenes (such as a serene Buddhist Zen Garden, a lush forest, or a photogrammetric treatment room) into the virtual realm and simulates digital twin experiences with sensing systems such as motion tracking or multimodal display, i.e., auditory, haptic, olfactory. Such spatial measures can effectively distract the patient's attention and increase self-recognition, thus motivating rehabilitation.

(3) **Attention focus:** Compared to AR, VR settings minimize the uncertainty and distractions (e.g., visual noise) associated with the external environment, thus allowing patients to focus entirely on the training task. Physical therapists can customize the visual focus in the virtual environment to direct the patient's attention to specific virtual events or visualizations by plans.

(4) **Scalability:** As treatment plans are dynamically adjusted, developers can adapt and deploy the latest training regimens in the VR interface to align with the patient's condition or motivational needs.

(5) **Quantify Subjective Experiences:** Most VR headsets are equipped with a sensing unit for directional tracking, 3DoF, allowing researchers to measure angular changes in the head around three axes, XYZ, of rotation. More advanced VR devices are configured with a 6DoF system that can measure six types of movements. Researchers can use infrared optical tracking systems to target specific points in 3D space on headsets. Therefore, with VR, movement behaviors are more easily tracked, measured, and analyzed. Researchers can reconstruct the first perspective view of patients and the third perspective behavioral simulation and analyze head movement frequencies, directions, and speed. These data are essential feedback for evaluating the subjective experience in VR prototypes.

(6) **Price:** The development of Cloud technology has driven down the cost price of VR devices. Shortly, more computing processes will be placed in the cloud to minimize operational requirements on hardware, which can significantly reduce manufacturing challenges. "Low price + portable" will promote VR devices as the following promising universal personal accessories.

2 Related Work

2.1 Virtual Reality in Healthcare

VR technologies redefined the horizons of healthcare-related fields with many successful attempts already underway. For example, VR addressed a wide range of physical rehabilitation needs, including stroke [20], brain injury [21], spinal injury [22], limb movement [23], and pediatric rehabilitation [24]. Several studies have shown that rehabilitation effectiveness will be significantly improved if multiple forms of feedback are provided via VR throughout the training process to stimulate the patient's initiative and advise on corrections. In response, Tyromotion developed a robotic upper extremity rehabilitation device integrated with VR interactive modules for stroke recovery [25]. The system provides haptic and audiovisual feedback to encourage users to modify motion range and repetition intensity for daily training tasks. Maggio et al. reported that VR could be an effective cognitive intervention to facilitate positive learning experiences for patients with traumatic brain injury [21]. Nissler et al. presented VITA, a multifunctional system that integrates VR displays with upper extremity intent monitoring and visualization programs for limb loss and functioning rehabilitation [26]. Brutsch et al. presented a robot-assisted treadmill training simulator augmented by a VR soccer game to treat neurological gait disorders in children [27].

Regarding psychological rehabilitation, VR was also implemented in exposure therapy to treat psychocognitive disorders, such as phobias [28], anxiety disorders [29], attention deficits [30], and Post-Traumatic Stress Disorder [31]. Furthermore, VR has many applications in the field of adjuvant therapy. For example, Blaha et al. developed a VR and Leap Motion-based eye-hand collaboration system that improved vision and depth perception in patients' amblyopic eyes [32]. Gromala et al. presented a multimodal virtual reality treatment for managing chronic pain [33]. Hoffman et al. presented a controlled study investigating VR as a nonpharmacologic pain management method [34].

Apart from rehabilitation, surgical synergy has also benefited from VR. For example, the da Vinci robotic surgery system, based on robotic surgery technology developed at MIT, was combined with virtual endoscopy technology to allow physicians to view a patient's organs in a virtual environment and operate a robotic arm to perform complex surgical procedures [35]. Gasques et al. studied Artemis, an AR-VR collaborative system that guides novice surgical practice [36].

Since motivation is a top priority in rehabilitation training, more studies consider VR and AR as incentive drivers that enhance participation. Researchers generally agreed that the combination of 3D simulation environments and gamification measures can encourage patients to complete tedious and repetitive movements or divert their attention to optimize the quality of therapeutic exercise. Mubin et al. integrated 30 works using gamification or virtual displays to aid robot-assisted exoskeleton training [37]. For example, Klamroth-Marganska et al. designed customizable VR games with different difficulty levels for arm motor impairment [38]. Khor et al. investigated a portable wrist-based rehabilitation robot and VR game interface to demonstrate the real-time multisensory feedback displayed in VR enhanced user engagement [39]. Alimanova et al. developed a Leap Motion Controller (LMC) supported VR game for upper limb rehabilitation [6]. Moreover, Hymes et al. designed a participatory digital game approach for patients with aphasia [40].

Following the existing research, this thesis investigated a VR rehabilitation interface, whose usability and functionality are augmented by the real-time sensing, monitoring, and visualization of motor and musculoskeletal feedback, regarding the unsupervised lower limb physical recovery.

2.2 Augment Reality in Healthcare

Augmented Reality (AR) is a reality-based interactive technology that extends a real-world user experience with computer-generated displays, sounds, text, and effects. Compared to VR, which aims to create fully immersive environments, AR addresses physical-virtual synergy and supersensory. AR had many successful practices in the fields of vital sign monitoring [41(p.)], tele-emergency care [42], healthcare education [43], and rehabilitation [44,45]. Research efforts in Rehabilitation generally focused on using AR to demonstrate virtual avatars, training tasks, and behavioral feedback for the purpose of educating, guiding, and encouraging patients. For example, in a motor learning scenario, Sigrist et al. showed that AR could enhance learning efficiency by helping users improve performance and acquire more complex skills [46]. In dealing with an upper and lower extremity therapy scenario after stroke, Gama et al. determined the effectiveness of combining a Kinect motion tracking system with an AR training feedback system for shoulder abduction therapeutic exercises [47]. Luo et al. reported an advanced environment that incorporated AR projections, body aligners, and pneumatic devices to assist hand rehabilitation training [48]. Jaffe et al. built an obstacle running treadmill to intervene and assess post-stroke gait training (i.e., speed, stride length, ability to cross obstacles, duration of persistence, etc.) [49]. Bruke et al. investigated two rehabilitation game tasks using a low-cost webcam and marker-based AR technology [50].

In particular, researchers have studied Augmented Feedback (AF). Several projects have found that AF positively affects motor control and learning correction. For example, Mumford et al. used a depth camera to track the marking behavior of hand controls and mapped a real-time projection of virtual feedback onto a tabletop to guide users through a progressive rehabilitation task. This approach has been proven to improve upper limb function [51]. In addition, Jakus et al. introduced a high-precision motion tracking and visual feedback system that supported multimodal concurrent feedback of auditory and visual projections [52].

However, within the paradigm reported in this paper, research will remain focused on VR as the display medium to reduce environmental noise from the physical environment and exploit the benefits of immersion.

2.3 Sensing Techniques for Unsupervised Physical Rehabilitation

The exponential growth of a wide variety of low-cost portable sensors has been witnessed in recent years. The rapid development of wearable sensing technology provided the technical prerequisite for the prevalence and progress of VR rehabilitation therapy. For example, researchers have used biosensors to track heart rate, gaze sensors to measure pupil movement, EMG sensors to acquire muscle engagement, and EEG sensors to monitor concentration rates. In most physical rehabilitation studies, motion monitoring remains a top priority. To achieve high-precision, low-latency monitoring, researchers have explored four major approaches: vision-based, force-based, inertial-based, and mixed methods.

(1) Visual-based sensors featured many consumer-grade sensing technologies that are widely accessible and adaptive to desktop or at-home rehabilitation scenarios. Depending on different user requirements for cost and performance, visual-based sensors could provide various solutions ranging from low-cost & low-accuracy to high-cost & high-accuracy. For example, Khademi et al. used commercial cameras to capture the hand posture of participants in desktop exercises and used the data to evaluate direct and indirect interaction tasks [53]. Chang et al. presented a physical rehabilitation system supported by a depth camera, Kinect [54]. Within the system, a machine vision algorithm monitored real-time motion data and exhibited visual recognizer indicating motion state and number of movements (e.g., upper or lower extremity movements). Virtual Rehab, a clinically proven system, also integrated Kinect with a customized virtual rehabilitation software [55]. Fernandez-Gonzalez et al.

investigated an upper extremity rehabilitation therapy based on Leap Motion, a commercial sensor device that monitors hand gestures [56]. Wang et al. explored the impact of combining Leap Motion and VR on enhancing training outcomes for stroke patients [57].

(2) Force-based sensors were typically employed in tasks that measure force intensity or with footwear. For example, Nintendo has developed a ring-shaped health device that consists of spring-like material and a highly sophisticated mechanical sensor that detects the force of pushing and pulling [9]. FlexiForce, another mechanical sensor, supported hand rehabilitation for rheumatism patients to perform multiple exercise tasks, such as pinching, gripping, and rotating [58]. Fransson also developed a Force Sensitive Resistor (FSR) based rehabilitation glove [59]. He indicated that selecting the appropriate configuration and type of mechanics sensor for different application scenarios is crucial. Sensor properties (i.e., *size*, *sensitivity*, *dynamic interval*, *accuracy*, *linearity*, *hysteresis*, *repeatability*, *resolution*, and *bandwidth noise*) will affect the quality of the final prototype. Kyto et al. presented another bimanual grip-supported prototype based on high pressure sensitive fabric [8]. In addition to these studies, researchers addressed footwear-based measures. For example, they investigated walking strategies with in-shoe pressure [60], gait training feedback [61], and standing posture measurements [62].

(3) Inertial sensors perceive movement trajectory and frequency by monitoring angular rate gyro or linear acceleration. For example, Nintendo developed Joy-Con, a fitness product with a built-in six-axis acceleration sensor and gyroscopic ultra-low-power MEMS inertial sensor [9]. Holden et al. introduced a wrist-based wearable device with inertial sensors and used the prototype to record daily behavior [63]. Lay-Flores et al. used a 9-axis Inertial Motion Unit (IMU) to record and store regular activity states of

motion [64], and Patel et al. explored that wearing inertial sensing in the home environment would be the most immediate way to prevent falls [65].

(4) To pursue more accurate motion tracking, researchers also discussed integrative and complementary measures of multimodal sensors. For example, Hondori et al. combined inertial sensors with depth cameras to track position, angular displacement, and acceleration on both sides of the body [66]. Segura et al. looked into integrating cameras with accelerometers in a wearable setup [67].

This thesis applied three sensing techniques to the VR rehabilitation system. They are the high-precision motion capture system based on multiple depth cameras (to track the real-time motion behaviors), the 6DoF inertial sensor built into the VR headset (to track and reconstruct the headset movements), and the wearable EIT device (to monitor the engagement of thigh muscle groups).

2.4 Muscle Engagement Sensing and Visualization Techniques

Research has shown that VR rehabilitation systems benefited from multi-dimensional sensing information and augmented feedback. Because muscle engagement is directly related to physical rehabilitation, muscle monitoring and display in a corresponding VR visualization setup would be of research relevance.

Electromyography (EMG) and Mechanomyography (MMG) are two leading techniques for monitoring muscle behavior. EMG records the bioelectrical signals generated by single muscle fibers during contraction to assess the functional state of the motor neurons and the target muscle pieces. MMG records the mechanical transverse vibrations generated by motor neurons through the activation of motor units triggering the contraction of muscle fibers. It has been found that multiple types of sensors can be used to measure EMG signals, for example, accelerometers [68], laser proximity sensors [69], capacitive sensors in a matrix [70], piezoelectric contact sensors (FSR) [71], etc. Compared to EMG, MMG has the advantage of customizable spatial resolution and sampling range, but both techniques are limited to sensing only contractile muscle activity and cannot respond to stretch.

Furthermore, because human muscle distribution is volumetric, both stated technologies capture only local muscle signals in the subcutaneous superficial layer but lack a global understanding of the connected muscle groups. Moreover, motion artifacts caused by real-world variables (i.e., electrode distribution) may severely impair the information in the surface electrophysiological signal or even occlude it completely. More recently, researchers have proposed more measurement modalities. For example, Muscle Contraction (MC) sensor is a mechanical sensing approach that used indirect measurements of the piezo-resistance between the muscle surface and the tip contact [71]. Hosono et al. also proposed a correlation study using IR sensor arrays, instrumentation sensors, and correlation calculations to estimate muscle swelling load [72].

In addition, Electrical Impedance Tomography (EIT) is a non-invasive, high-resolution way of monitoring muscle engagement. This technique measures the current (voltage) induced at the body surface by injecting a known voltage (current) into the muscle, calculates the impedance distribution of each tissue and organ under the action of an electric field within the body following the reconstruction algorithms, and finally produces a tomographic image. Studies have shown that EIT has notable superiority in monitoring the depth information of muscle groups and muscle activities under contraction and stretch [73(p.)]. Since the measurement basis of EIT is derived from bioimpedance and not neural activity as in EMG, it is more robust against motion artifacts. In addition, it has already been widely used in several wearable scenarios. For example, Zhang et al. developed an EIT-based gesture recognition wristband [74]. Romsauerova et al. worked on an EIT-based head setup that allowed monitoring of brain lesions [75]. To perform stereoscopic investigations of the head, the authors applied medical electrodes all over the head to achieve multi-frequency EIT imaging. Other researchers were dedicated to developing hardware devices that have been commercialized or open-sourced. For example, Zhu et al. presented an open-source toolkit for producing EIT prototypes, including a 3D editor for designing wearable devices with embedded electrode arrangements, EIT sensing boards, stacked multiplexer boards, and an Arduino-based EIT Sensing library, and a mobile image reconstruction API [73].

More work presented signal visualization tools. In addition to the visualization software that accompanies the commercial hardware, several open-source reconstruction libraries are available. For example, *EIDORS* [76] offered free MATLAB-based [77] computational software for EIT technology for medical and industrial scenarios. *OpenEIT*, an open-source EIT imaging hardware suite, was configured with a custom visualization software framework [78].

3 VR Rehabilitation Simulator

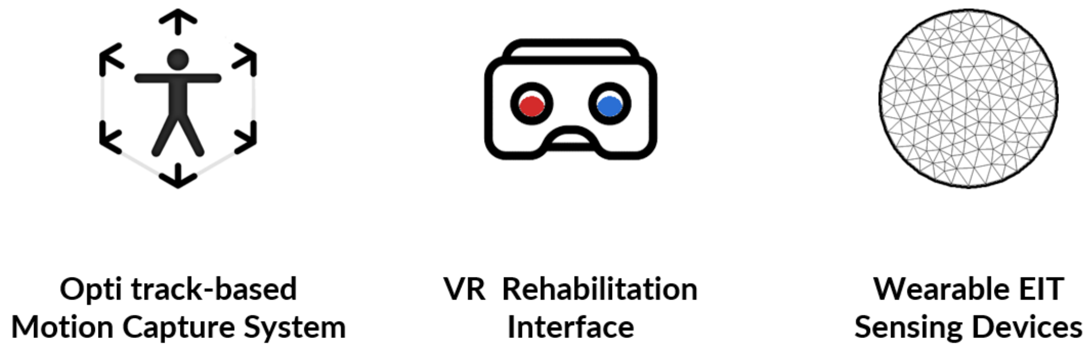

Figure 2 VR Rehabitation Simulator

This paper introduced a VR rehabilitation simulator that integrated motion tracking and muscle engagement sensing with augmented feedback visualization. This study prototype is applicable to lower extremity rehabilitation scenarios and can be applied as a template for general physical rehabilitation training. It is a three-in-one input and output system consisting of (1) a VR rehabilitation interface featuring a training regimen protocol panel, a standard motion reference panel from a physical therapist, a streaming patient avatar driven by real-time motion and muscle engagement data, a muscle visualization panel, a text-voice exercise instruction panel, and a simulated training environment carrier, (2) an OptiTrack-based high-precision optical motion capture system, (3) and a thigh-based EIT sensing device for configuring muscle engagement behaviors.

3.1 Two Input Systems

3.1.1 Thigh-based EIT Sensing Device

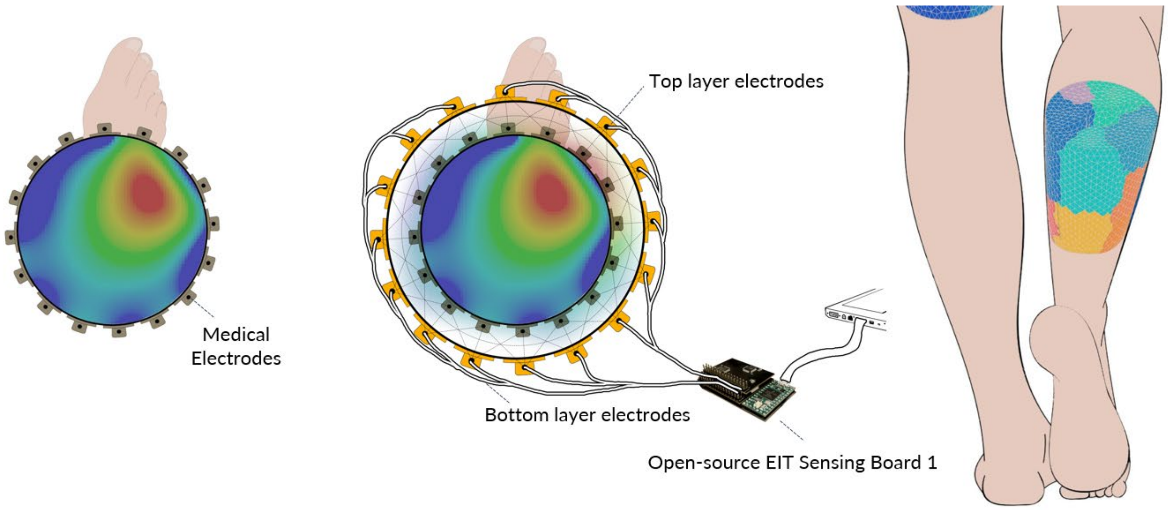

Figure 3 How Electrical Impedance Tomography (EIT) work?

The VR simulator used the EIT boards developed by EIT-Kit [73], an open-source toolkit presented by *MIT HCI Engineering Group*. The hardware collection consisted of a motherboard for sensing, computing, and calibrating EIT signals and a stack of 32-to-1 analog multiplexer boards that allow modular configurations. Its technical implementation has the following features that perfectly support the muscle engagement input requirements of this work.

(1) **Scalability:** Multiplexer boards can be stacked to extend the core sensing board and support up to 64 electrode channel configurations for EIT signals. This plug-and-play design improved the sensing image resolution and enabled multi-layer electrode deployment (up to four-layer structures) for measurement. In the specific case, the VR simulator used 32 electrode channels.

(2) **Customized calculation:** Impedance measurements are influenced by various factors, such as individual differences of users, electrode contact size, distance of neighboring electrodes, or monitoring frame rate. The hardware is adaptive to those conditions because it adjusts the input AC current up to 500 kHz for voltage output (-

5v to 5v), as well as supports the automatic calibration of the output data through adjustable instrumentation amplifiers (for differential voltage control) and digital rheostats (for differential current control). Therefore, the features help the VR simulator achieve accurate impedance calculations in the following user research. As advised by the developer, the EIT device used a 50 kHz signal frequency that is most favorable for human skin.

(3) **Advanced version:** The EIT hardware used in this work is an iterated version with high frame rates [12]. The new implementation used *Teensy 4.0 Microcontroller* [79], added a separate Bluetooth communication module, and reduced SPI channels. With the improvements, the VR simulator can be supported with faster processing capability and more stable data sampling, synchronization, and transfer rates when conducting user experiments for hours.

(4) **Volumetric measurements:** Many EIT applications used only single-layer electrode deployment, and therefore only flat images of muscle cross-sections can be reconstructed. However, to enhance the robustness of the EIT signal to uncertainties during motor training (e.g., electrode displacement) and enable stereoscopic sensing and visualization of every muscle group, the VR system requires a volumetric EIT reconstruction solution. The sensing boards of the EIT-Kit supported two modes of AC signal injection and voltage measurement: 2-terminal and 4-terminal. In the conventional 2D EIT reconstruction mode, the algorithm calculates the voltage behavior of the remaining electrode groups based on the injected AC signal between adjacent electrode groups. In this flat sampling mode, the deployment of electrodes with additional upper and lower layers of structure does not address the regional activity of deep muscles. To return volumetric resistance between electrode layers, electrodes should be deployed in a counterclockwise "square" pattern. The electrode

configuration also followed the "skip 4" structure [80]. Overall, the simulator is based on the 4-terminal mode, 32 electrode channels, and two layers of 16-electrode arrays.

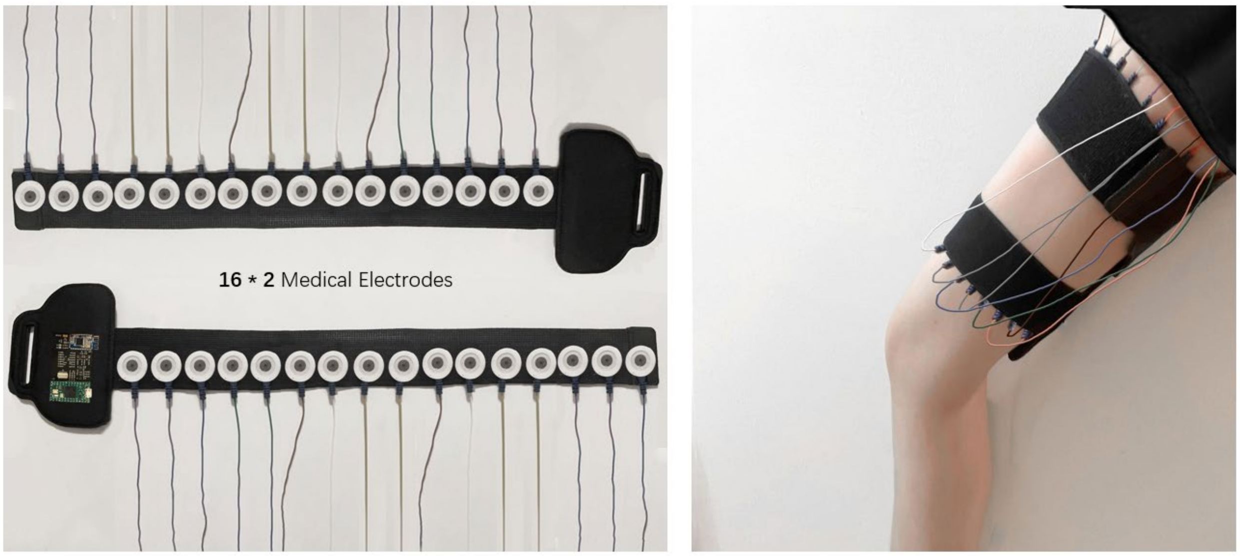

Figure 4 Thigh-based EIT Sensing Prototype

The follow-up user research focused on lower extremity exercises that primarily trigger thigh muscles. Thus, in this wearable setup (figure 3), two rows of evenly distributed 16-electrodes arrays was attached to the upper and lower human thighs and connected to the multiplexer board with approximately 40 cm long interface cables. To keep the relative positions of the electrodes not deforming in motion and applying uniform forces, the wearable prototype covered a leg strap accessory of elastic textile fabric and a Velcro fastening on the electrodes.

3.1.2 Optical Motion Capture System

3.1.2.1 OptiTrack

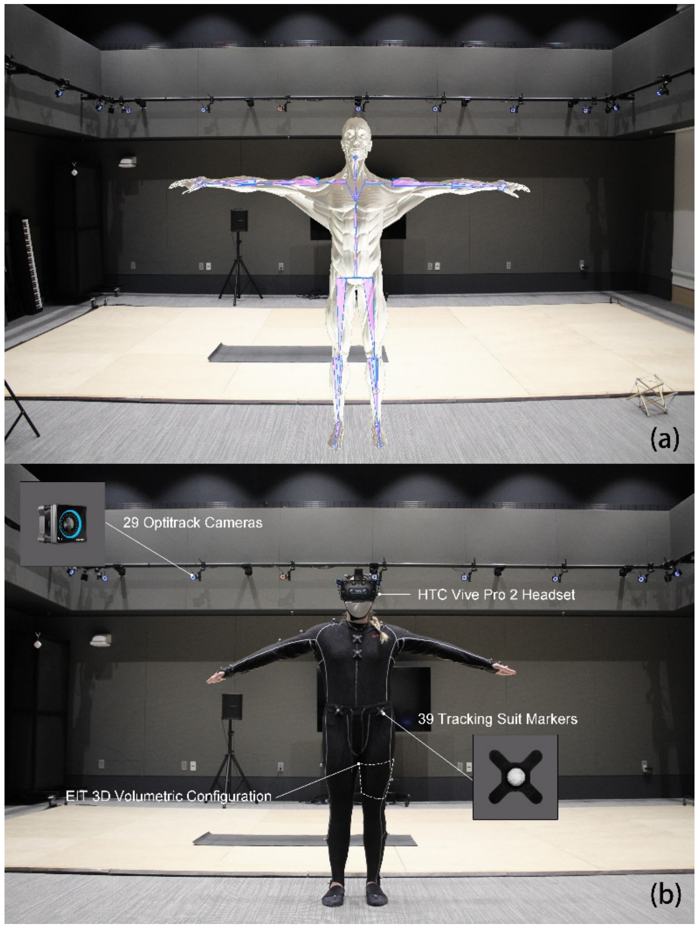

Figure 5 OptiTrack Motion Tracking System Setup

The VR rehabilitation prototype implemented the motion tracking system with OptiTrack [81]. The system includes a central processing unit, 29 high-precision 850mm infrared cameras (Prime-13) with 250 frame rates, Motive processing software [82], and a Velcro-made tight-fitting tracking suit and accessories. Each camera is controlled by a central processing unit, which synchronizes the dynamic image acquisition of fixed and highly reflective markers on the body surface. With an infrared light filter, the camera can capture the markers emitting infrared light in space while filtering out background noise and improving the signal-to-noise ratio of the acquired input. This passive infrared optical motion capture system is positioned using a global shutter scheme: all elements are exposed simultaneously to ensure no motion blur in the image. In addition, since the OptiTrack system always obtains the absolute position coordinates of the markers in the current space, the accumulated errors are optimized to a minimum. In the following user research, the motion tracking system returned motion errors of up to 0.5 mm at long distances.

For various research purposes, the VR simulator primarily used the following features of Motive processing software: asset generation, pose calibration, movement pre-recording, streaming, and export.

(1) **Asset generation:** In Motive, more than ten skeleton templates were designed to conform to the biomechanical marker distribution and provide information on different marker settings. While markers are the basis for motion tracking, marker settings of appropriate size, roundness, and reflectivity significantly impact motion tracking quality and reliability. While suiting up participants in the following user research, all markers must be firmly fixed to the surface of the tracking body to prevent any deformation. In addition, the markers on the left and right sides of the skeleton were deployed asymmetrically to distinguish the target orientation. The VR system selected the standard template containing 39 markers for the Conventional Full Body collection. It used a total of 32 7.9mm (5/16'') 3M Markers and 6 6.4 (1/4'') 3M Markers fixed for the body and joints of every participant [83]. By identifying the correct markers and an initial T-pose, Motive allowed the VR simulator to create and store the virtual avatar skeleton of every participant.

(2) **Pose calibration:** Although OptiTrack introduced automatic calibration, pose distortion caused by marker occlusion during exercise execution is inevitable. Thus, manual calibration allowed the VR simulator to reactivate OptiTrack cameras, clear noises, and re-anchor each bone and joint position.

(3) **Motion pre-recording:** The recording feature helped the VR simulator capture and store the therapist's standard motion sequences, mapped them to a custom skeletal architecture, and presented the rigged avatars in the 3D display. The pre-recording data contained 3D coordinates and movements of full-body markers, which allowed the system to preview, post-edit, and reconstruct the recorded movements on multiple platforms (i.e., Blender and Unity in this case).

(4) **Streaming:** The VR simulator used a streaming engine, streaming IP transport, to capture, transmit, and render real-time motion trajectories of participants to a cross-platform (Unity). In Unity, the streaming motion was targeted on a customed avatar, with another therapist's avatar displaying pre-recorded motion reference in parallel.

(5) **Export:** The VR system exported BVH files and infrared camera video files for post-processing.

3.1.2.2 A Kinect-based Alternative

Due to user research requirements, the high precision and low latency technology offered by OptiTrack was significant, but it had disadvantages of accessibility. A functional OptiTrack system needs to be supported by eight to dozens of cameras, each costing several thousand dollars. Although cost-effective alternatives, such as *Vicon* [84], have a relative price advantage, both systems are not appropriate for at-home rehabilitation scenarios that should be widely applicable. Therefore, the thesis investigated a low-cost motion capture alternative (~ $40) based on a commercial depth camera and an open-source software package. While reducing the cost will affect accuracy, it makes the VR prototype more accessible and allows for greater freedom in software-side development.

This low-cost setup was composed of a suitable area, a KinectV2 camera (independently illuminated IR @ 30fps), Kinect for Windows SDK 2.0 (Kinect Studio), and a target avatar in Unity. First, KinectV2 projected modulated near-infrared light through an infrared emitter, which was reflected when it hit users. The IR camera received the reflected light, used TOF technology to measure the depth and calculate the reflection time difference, conducted background segmentation to create a mask and identify the subject outline, and then transmitted the 3D depth map based skeletal tracking imaging to the Unity interface. In this case, KinectV2 can detect color maps at 1920x1080@30 fps, depth maps at 512x424@30 fps, and record 25 human body joints. In addition, like Motive, Kinect Studio supported 2D and 3D skeletal motion information preview, pre-recording & post-editing, real-time streaming & cross-platform communication, and exporting.

Because Kinect has been widely studied in HCI, a Kinect-based VR rehabilitation simulator presented fewer technical obstacles and greater extensibility for a broader developer community. For example, I employed *Visual Gesture Builder* [85] with Kinect to create a pose classifier that allowed gesture detection and awareness while users performed exercises. To achieve this, Kinect Studio recorded motion files for specific therapeutic exercises and repeated the sampling multiple times to increase the overall sampling number. 2/3 of this data was used for training, and 1/3 was used for testing. The higher the final confidence value obtained, the better the current test movement meets the training accuracy criteria. Then, while this classifier (.gba/.gbd format) was stored and enabled in Unity, a visualization indicating the current gesture status was displayed in the VR environment. Future researchers can explore more Kinect-based attempts, such as investigating specific feature extraction and computation for critical joints (i.e., distance and pinch angle relationships) for more detailed motion evaluation feedback.

3.2 Virtual Reality Interface

3.2.1 Formulative Study

Before describing implementation details of the VR interface, outlining the design principles of the VR-based rehabilitation environment is instrumental, as it will help the thesis and future research establish the correct preconceptions and conduct self-assessment and detailed review of the final VR deliveries.

In contrast to traditional physical spaces, virtual rehabilitation space design is under-explored. Many institutions and researchers, such as Microsoft [86], Google [87], Leap Motion [88], etc., have published design guidelines for general VR environments, but these principles are usually not scenario-specific. Therefore, this thesis aims to determine a design paradigm that could facilitate decision-making while designers construct a VR rehabilitation space.

Participants: 3 participants (2 Males and 1 Female), aged between 23 and 27 years, participated in the research. All participants held design-related degrees and had experience creating or using VR. Of these, all reported that they exercised regularly, and two had previous experience in physical rehabilitation.

Setup: An early VR prototype was built in Unity based on five design elements: *Environmental Model*, *Spatial Dimension*, *Lighting Condition*, *User Interface Layout*, and *Interaction Method*. Each design element contained three asset profiles that customized experiential properties. For example, the prototype equipped three scale settings, *Large*, *Medium*, and *Small*, for the element of *Spatial Dimension*. Through toggling the *GameObjects* of asset profiles in Unity, the researcher presented asset profiles for each element in an additive sequence. Participants reviewed profiles in elemental order. They verbally reported and rated profiles that they considered optimal within every elemental condition. After every selection round, the VR display remained in its current choice, and the researcher superimposed the profiles of the second elements on the current scene. The study was completed once participants reviewed all design elements. In general, the system had 15 (5 * 3) design profiles that could be layered to create 3^5 highly customizable additive prototype combinations.

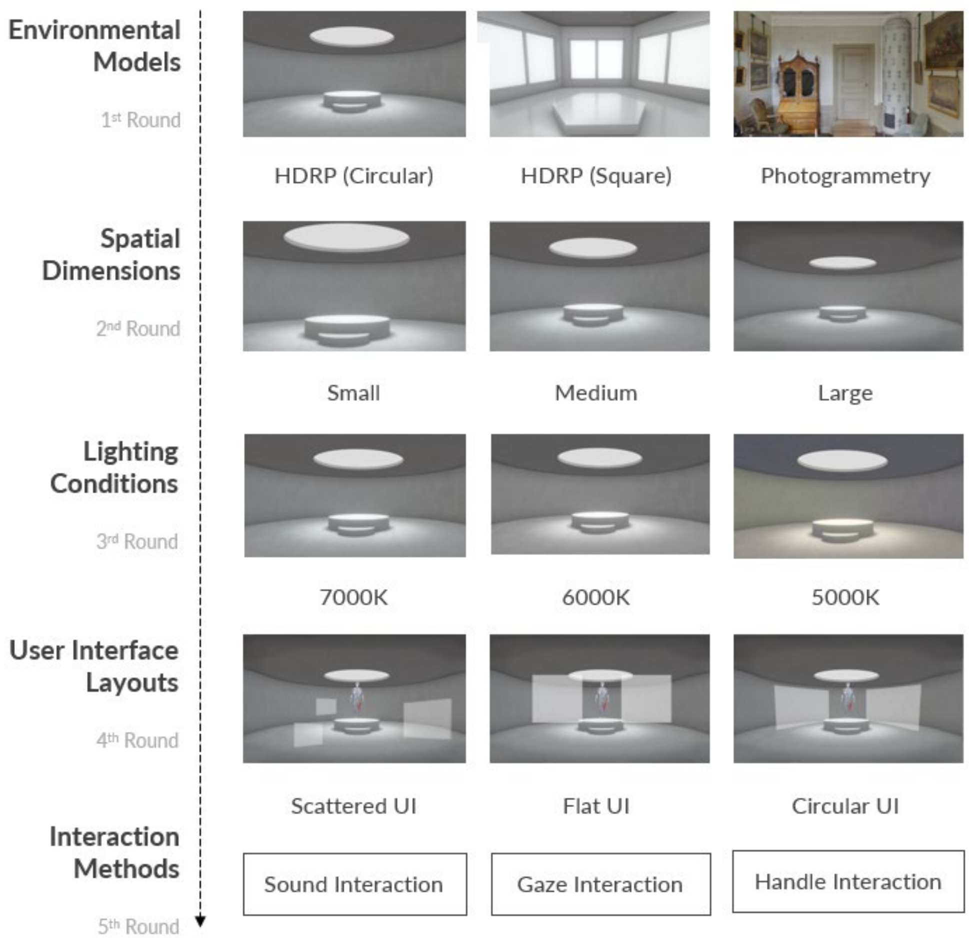

Figure 6 Design Elements and Profiles

Procedure: Participants performed exercises while they were presented with VR display. The following is a detailed study process: Participants were first immersed in three virtual *environmental models*, a photogrammetric model, a High Definition Render

Pipeline(HDRP) model with a circular form, and a High Definition Render Pipeline(HDRP) model with a square form. They previewed each environmental model for 15 seconds, chose the most favorable profile, and rated every option. After anchoring the current decision, the researcher then showed the participants the selected model with three *scale settings*, Large (~1000sqft), Medium (500sqft), and Small (200sqft). Then, they continued to compare l*ighting conditions* among warm white light (5000K), daylight (6000K), and cool white light (7000K), *UI displays* among circular menus, flat menus, and scattered menus, and *interaction methods* among handle interaction, gaze interaction, and sound interaction. The display order was randomized to avoid order effect. Moreover, the researcher conducted about 10-15 min of one-on-one interviews with each participant to understand their deeper motivations for making design decisions.

P#	Environmental Models			Spatial Dimensions			Lighting Conditions			User Interface Layouts			Interaction Methods		
	HDRP (CIR.)	HDRP (SQ.)	PHOTO.	LARGE	MEDIUM	SMALL	5000K	6000K	7000K	CIR. UI	FL. UI	SC. UI	VOICE	HANDLE	GAZE
P1	4	2	3	3	4	2	3	5	3	4	2	3	4	2	3
P2	4	4	3	4	3	3	2	3	4	5	3	3	3	1	4
P3	3	4	5	5	3	1	3	4	2	4	3	3.5	2	3	5
Average	3.7	3.3	3.7	4.0	3.3	2.0	2.7	4.0	3.0	4.3	2.7	3.2	3.0	2.0	4.0
SD	0.5	0.9	0.9	0.8	0.5	0.8	0.5	0.8	0.8	0.5	0.5	0.2	0.8	0.8	0.8

Table 1 Design Profiles Evaluation

Quantitative Result: Table 1 presents the rating results for each asset profile of five design elements. In summary, participants recommended the HDRP model with circular form (3.7, SD = 0.5), Large scale (4.0, SD = 0.8), 6000K Lighting Color (4.0, SD = 0.8), Circular UI Menu (4.3, SD = 0.5), and Gaze Interaction (4.0, SD = 0.8). Especially, all participants agreed on circular menus as the optimal UI display option.

Qualitative Findings: The researcher interviewed participants to understand their design decisions comprehensively. The final design of the VR simulator also considered the following design guidelines regarding recurring thematic ideas.

(1) **Space as background:** While the flexibility of simulated scenes is the core strength of VR as a display medium, the driving force for patients to use the rehabilitation space is to engage in therapeutic exercise. Therefore, the environment design should add value to the content rather than overwhelm it [89]. P1 suggested: "overly detailed simulation environments can distract people from focusing on exercises, which is a disadvantage of the photogrammetry model." P2 further added: "The background should not include any fancy elements in motion, which can easily cause vertigo."

(2) **Appropriate spatial properties:** Unreasonable spatial dimensions and unnatural light settings will require additional time for users to adapt. P3 said: "Theoretically, a vast space will be superior to a narrow space when in motion, but do not exaggerate any properties."

(3) **Visual focus at the center:** Because of the technical limitations of VR headsets (the maximum FOV of HTC VIVE Pro is about 120 degrees in horizontal and 97 in vertical [90]), the way participants observed the VR world is different with a real-world scope, which is constrained from the center. Therefore, designers should spotlight high-priority information in the vision center and adjacent areas and put relevant information in proximity.

(4) **Natural interaction:** All participants indicated that interactions in motion should be as effortless as possible. P2 and P3 strongly preferred gaze interaction, believing it to be the most inclusive and high responsive method. However, P3 reported that the gaze pointer was too sensitive. In response to this concern, iterations were made in the final VR implementation.

3.2.2 Implementation

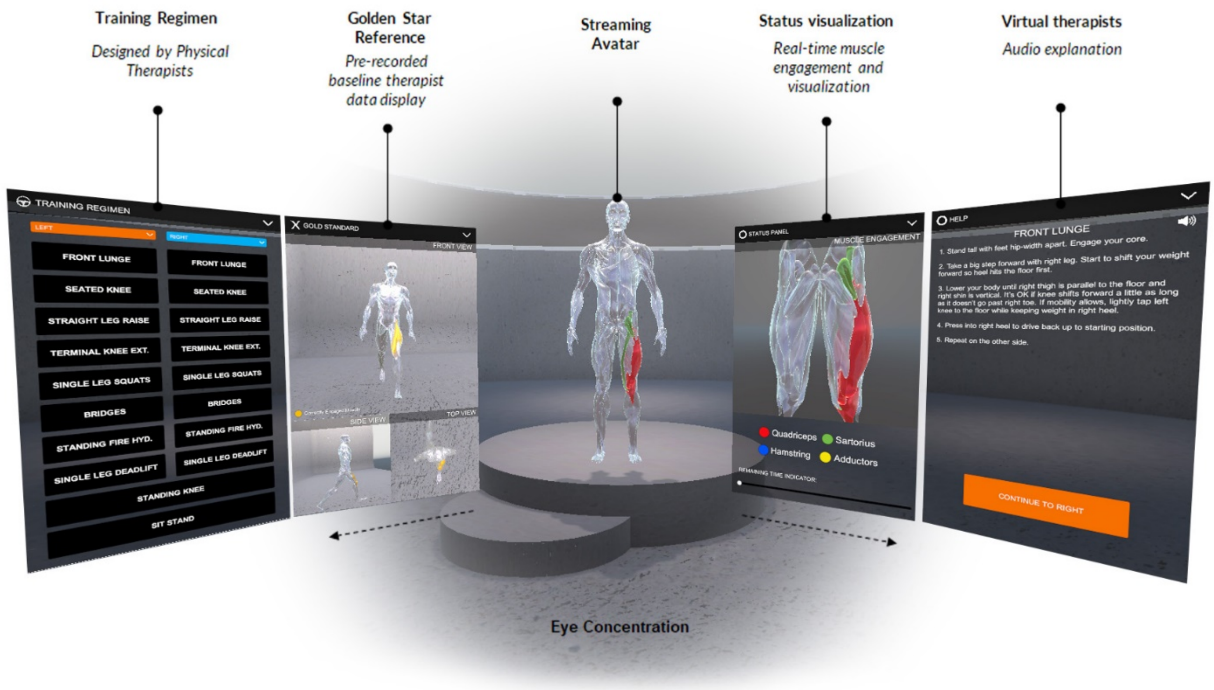

Figure 7 VR Rehabilitation Simulator Interface

The final VR prototype is based on Unity and the HTC VIVE Pro 2 headset [91]. For environment design, it applied a High-Definition Rendering Pipeline (HDRP) rendered rotunda model (Large size) and six 6000K overhead lights. For the user interface, it featured four circular floating UI menus. As shown in figure 7, the left-most panel introduced a training regimen containing ten therapeutic exercises for the lower extremity, which is required for Total Knee Arthroplasty(TKA). The first eight exercises are for single leg training, and the last two are for two legs training. The adjacent panel presented a physical therapist avatar rigged by pre-recorded gold standard motion reference. The front, left, and top camera views were captured for an all-angle observation. The therapist avatar automatically triggered the corresponding motion animation when participants clicked the training list. Meanwhile, tackling muscle groups were highlighted while users perform exercises with the simulator. Moreover, the panel against the right side of the center showed a close-up window, a color-coded muscle engagement visualization viewport. Each muscle group was modeled separately to achieve the one-to-one matching and driving effect between EIT sensing and muscle pieces. The muscle engagement data was sampled with the wearable EIT device, mapped to corresponding muscle groups, and assigned different colors to muscle pieces as activation indications. For this simulator, the activation of *Quadriceps* was represented by red, the *Sartorius* by green, the *Hamstring* by blue, and the *Adductors* by yellow (figure 8). Darker color signified that the muscle was more contracted or stretched; if the color did not change, then the muscle group was not aroused. In addition, the UI interface on the far right contains detailed execution steps for each therapeutic exercise in audio and text formats. Patients used this panel for self-correction on posture when negative feedback of muscle engagement information was recognized.

Moreover, there was a full-body patient avatar driven by real-time motion tracking placed in the central stage area. The avatar was based on an average, high-precision adult model of 304 muscles based on the BioDigital library [92]. After completing the modeling in Rhino3D [93], the researcher imported the muscle model into Blender, an open-sourced motion graphics editor [94]. Then, the researcher used Autorig Pro [95], a Blender plugin, to define the original muscle model into joint-based skeleton, bind the armature, retarget pre-recorded animation, and finally export to Unity in .fbx format. This model carried both the therapist avatar at the left and the patient avatar at the center. The therapist avatar read and bound the pre-recorded baseline animations, while the patient avatar did not configure for any pre-set movements but only received streaming motion data from the

OptiTrack system. The patient avatar connected Motive via a streaming IP address, which allowed Unity to communicate with OptiTrack-captured 3D positions and rotations of joints and marker IDs. Moreover, the patient avatar also connected MATLAB, which transmitted muscle engagement data, an array of 8 EIT values, each ranging from -1 to 1 (-1 being 100% stretch and 1 being 100% contraction), corresponding to the engagement of 8 muscle groups on both thighs. Given these two inputs, Unity can display real-time motion and muscle engagement information on the patient avatar model.

Furthermore, this VR interface opted for gaze based interaction instead of voice commands and traditional handle control. To achieve this, the 6DoF inertial sensor built into the VR headset reads head (eye) rotation information off the center of the line of sight and detects whether the extended line of sight collides with the triggerable UI.

3.3 Muscle Engagement Visualization

Visualizing muscle engagement feedback required a cooperative effort of wearable EIT sensors, MATLAB-based volumetric EIT reconstruction algorithms, and Unity parsing programs. First, the user wore two layers of medical electrodes as input touchpoints on the thigh area. MATLAB received real-time streaming EIT data(the voltage measurements) from the sensing device and calculated the stereoscopic conductivity distribution for each voxel in the measured region. This parsing step involved the mapping from the physical muscle voxel to the reconstructed image boundary. To obtain more accurate results, the algorithm imported a customized Biodigital-compliant anterograde model of the mid-thigh for defining the virtual boundaries. The model consisted of four core muscle groups: *Quadriceps, Sartoris, Hamstring*, and *Adductors*, which are consistent with the structure of the patient and therapist thigh models used in the VR interface.

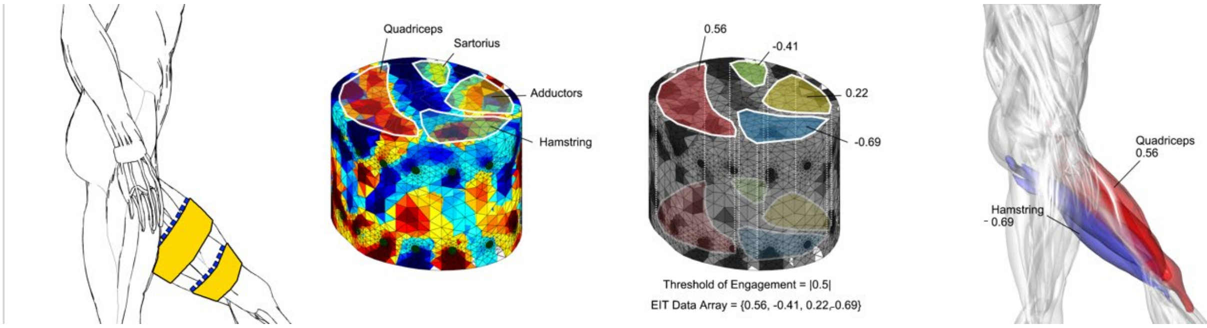

Figure 8 Muscle Engagement Visualization Workflow

Furthermore, because of individual biological differences, each participant had a different starting value and initial ratio of electrical conductivity in their muscles. Thus, the MATLAB program calibrated and normalized itself to adapt to personalized initial values and eventually remapped the differential conductivity change for each muscle volume to -1 o 1 (-1 indicates 100% stretch and 1 indicates 100% contraction). Then, Unity determined if the corresponding value for a particular muscle was greater than Abs (0.5). If the EIT value exceeded the threshold range of -0.5 to 0.5, then the muscle pieces of the patient's avatar will be rendered with the corresponding color coding (red, green, blue, yellow) and brightness coding (the darker, the more it deviates from the threshold); conversely, the system determined whether the muscle is not activated.

3.4 Technical evaluation

The VR simulator ran on a desktop computer with an NVIDIA GeForce RTX 2080 Ti graphics card. Given this hardware, researchers kept the system running for 1.5 hours, the minimum unit time to complete a single user study and evaluated the performance of the system as a whole and of each component. The capture speed of the infrared camera of the OptiTrack system was ~250fps, the real-time motion data transfer from Motive to the VR environment ran at ~90fps, and the rendering execution speed of the HTC VIVE Pro 2 VR headset was ~87fps. In addition, the EIT input muscle engagement data stream for wearable sensing inputs was ~26.94fps, MATLAB pre-processed 3D volumetric resistivity at ~7fps, and finally mapped the relevant information to the virtual avatar at ~5fps. Considering additional buffering area for Unity operation space, the EIT data stream communication was set at ~3.3fps in the subsequent experiments. The position and angular data of VR headset movement will be stored locally at ~5fps.

4 Study 1

The primary goal of this study is to investigate whether the VR rehabilitation simulator with augmented two-dimensional sensing technologies and visualization played a positive role in improving exercise execution accuracy during unsupervised physical rehabilitation. The thesis compared the VR simulator with motion simulation and muscle engagement visualization with the traditional motion-only interface through a controlled study. This study was conducted in collaboration with a licensed therapist who had practiced in the lower extremity rehabilitation domain for more than five years. With the expert advice, the research focused on lower extremity rehabilitation and selected ten therapeutic exercises from the Total Knee Arthroplasty (TKA) [96] protocol as a regimen.

4.1 Study Design

Study 1 recruited 10 participants (4 females, 6 males) aged 20-26 years (M=23.4, SD=1.96) from the local university. Their average height was 170.4 cm (SD=10.62), and they did not report lower extremity disability. Eight participants were right-handed, while the remaining two were left-handed. Eight participants had experience in VR. Four participants had received lower extremity rehabilitation training under the guidance of a professional therapist. Three of them had ongoing regular lower extremity rehabilitation. Because none of the participants were patients, Study 1 required them to use their non-dominant leg for exercise execution and designed three advanced tasks accompanied by the seven entry-level tasks to increase the difficulty of the exercises.

Study 1 designed a controlled study that presented participants with two VR display conditions, (A) motion simulation + muscle engagement visualization condition and (B) motion-only condition. In condition (A), the simulator displayed all UI panels in the VR interface of a training regimen, a pre-recorded motion reference from the therapist, a patient avatar with real-time feedback on muscle status and posture, a close-up color visualization of engaged muscle groups, and a text-voice exercise guide. In the case of condition (B), the VR interface only displayed the therapist avatar for reference and a patient avatar with motion mapping, which is similar to how the existing VR rehabilitation system delivered their measurement. In addition, participants wore the EIT sensing device throughout both conditions, allowing the researcher to track muscle performance with consistent quantitative measures.

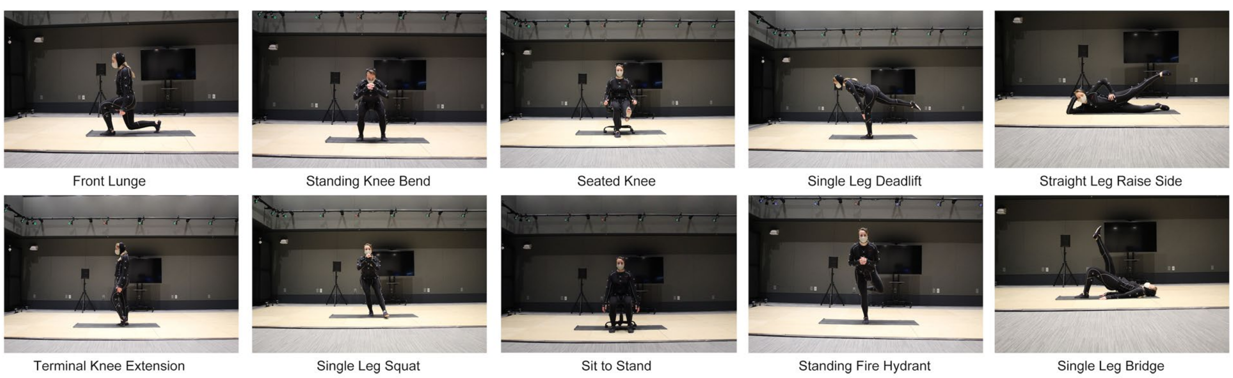

Figure 9 Physical Therapists Recording Motion Data

Baseline motion data as reference: Before the user research, a professional physical therapist engaged in lower extremity rehabilitation was recruited to record the gold standard baseline exercise. The total duration of the recording was 2 hours. The therapist wore a tracking suit and performed ten repetitions of 10 lower extremity exercises. Then, these pre-recorded exercise data were actuated on the therapist avatar and presented to participants in the following user research for more precise postural reference. Moreover, therapists provided knowledge about the target muscles for each exercise. The information was documented and logged as a data sequence into the Unity program.

When different exercise tasks are activated, both the movement animation and the highlighting of the corresponding muscle groups used will be performed on the therapist avatar.

Procedure: The user study lasted 90 minutes for each participant, and the procedure was divided into three steps.

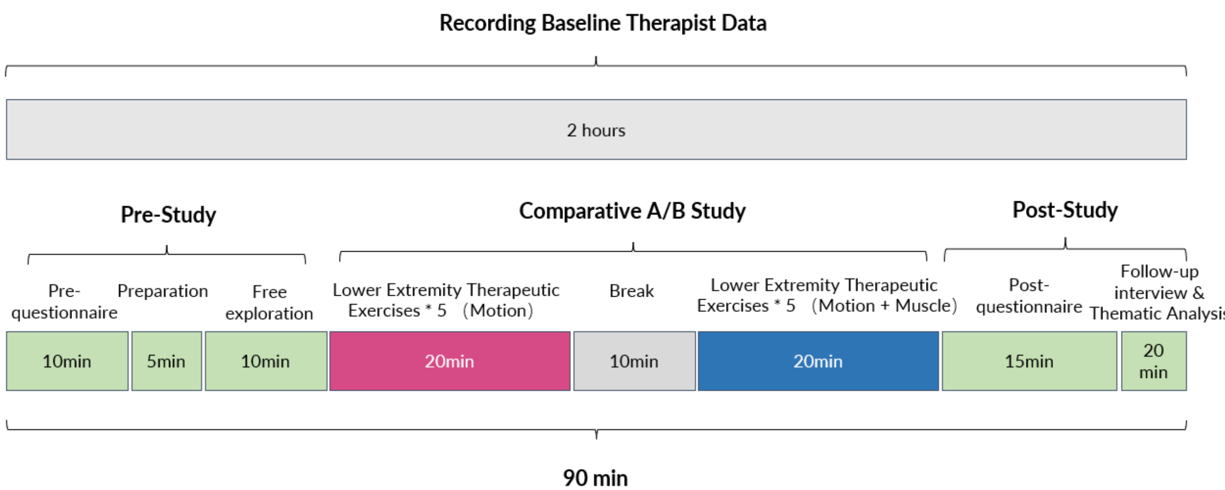

Figure 10 Study 1 Procedure

(1) **Pre-study (~25 min):** A pre-study questionnaire was given to the participants inquiring about demographic information, familiarity with VR and sensor use, and unsupervised rehabilitation experience. Then, two researchers helped participants wear an EIT device with 32 3M medical electrodes on their non-dominant leg and a tight-fitting tracking suit with 39 markers. Participants posed in T-Pose for initial OptiTrack sensing and tracking setup. One researcher entered full-body marker information to Motive as the basic computational elements to generate a real-time driven virtual avatar. The other researcher asked participants to perform an attempted lower limb movement while calibrating the baseline conductivity of the muscles on a MATLAB program for individual adaption. Afterward, the participants put on the HTC VIVE Pro 2 VR headset. They were given 5-10 minutes to familiarize themselves with

the environment, operate the interface in advance, and warm-up. Specifically, a researcher explained every UI panel and instructed thigh muscle distribution knowledge and the color-coded visualization rules of muscle engagement.

(2) **A/B Comparative study (~50 min):** A licensed therapist advised in selecting exercise ranges including seven tasks from the Total Knee Arthroplasty (TKA) protocol and three suggested progressions for the lower extremity rehabilitation. The ten exercises were divided into Group 1 [*Front Lunge, Standing Knee Bend, Seated Knee, Single Leg Deadlift, Straight Leg Raise*] and Group 2 [*Terminal Knee Extension, Single Leg Squat, Sit to Stand, Standing Fire Hydrant, Single Leg Bridge*]. The grouping criteria balanced factors such as postural diversity within the group (three standing exercises, one sitting, and one lying down), distribution of target muscles, and execution difficulty. Participants completed all therapeutic exercises in both groups and performed ten repetitions of each execution in comparative conditions. To control for the effect of individual variables on experimental outcomes, the study followed a 2x2 within-subjects design: participants performed Group 1 and Group 2 exercises, but the order of the two sets of exercises was randomized, and the sequence of which set of exercises was assigned to which study conditions were also adapted. Before each exercise began, the researchers informed participants of the target muscle groups to focus. Participants took approximately 1 minute to complete each exercise (ten repetitions). Following every individual exercise, participants rested for two minutes. A 10-minute break was taken between A/B conditions.

(3) **Post-study (~15 min):** After the experiment, participants received a post-questionnaire containing five scoring questions, three multiple-choice questions, and four subjective questions. These questions surveyed the overall usability and capability evaluation of the VR rehabilitation simulator, the rehabilitation experience

in both A/B conditions, self-performance measurement, and iterative recommendations.

Data Collection: Study 1 recorded four types of quantitative data: EIT sensing data (.txt), VR headset motion data (.csv), whole-body motion data (.bvh/.fbx), and on-site video (.mov). The researchers can reconstruct the whole process of the user study with the compositional support of these data. Full-body motion data was captured by the recording feature of Motive software; EIT data was sampled every 300ms by MATLAB; VR headset data was read by Unity and stored every 500ms; the training video of the participants was recorded by a 4K camera throughout.

4.2 Study Results

Exercise Type	Motion Only	Motion + Muscle Vis.
Front Lunge	59.13%	72.02%
Standing Knee Bend	44.92%	61.58%
Seated Knee	47.51%	59.52%
Single Leg Deadlift	41.16%	72.42%
Straight Leg Raise Side	48.00%	67.89%
Terminal Knee Extension	54.82%	54.84%
Single Leg Squat	55.58%	53.31%
Sit to Stand	66.31%	36.01%
Standing Fire Hydrant	54.29%	76.07%
Single Leg Bridge	28.61%	96.55%

Table 2 Exercise Execution Accuracy Comparison in both conditions [12]

Condition Evaluation: Study 1 validated the effectiveness of augmented muscle visualization in the VR simulator by assessing the accuracy of exercise execution, i.e., target muscle engagement, in both conditions. The accuracy was measured as the ratio of time triggering the correct muscle group to the overall exercise time. The results are shown in Table 2. In specific, in the motion simulation and muscle engagement visualization condition, participants reported a positive feedback rate of 65.02% (SD=16.16%). The motion-only condition was 50.03% (SD=10.51%). This improvement was statistically significant (p-value = 0.024), confirming that muscle engagement and movement simulation can complement input measures to improve the VR simulator performance. This difference was even more pronounced in the case of challenging exercises such as *Single Leg Deadlift, Standing Fire Hydrant,* or unconventional exercises such as *Straight Leg Raise and Single Leg Bridges,* which required participants to lay down. This indicates that the VR rehabilitation system is potent in training unfamiliar and complex exercises. Another direct evidence is that participants performed the first five repetitions with significantly lower accuracy than the last five movements. However, the entry-level task, *Sit to Stand*, returned the opposite result: participants demonstrated better compliance in the motion-only condition than in the combined condition. The exceptions may result from the fact that the exercise arose too easily and frequently in daily life, thus creating a high degree of muscle memory constraints that caused challenges for self-correction. Another reason could be that when participants wore VR, they were uncertain about the physical environment (e.g., fear of chair movement) and thus were distracted from standing to sitting.

The results of the qualitative feedback kept consistent with the data. In the post-questionnaire responses, the motion simulation and muscle engagement visualization conditions were unanimously favored by all 10 participants, and they all agreed that they performed better in this condition. For example, P6 stated: "Whether or not it helped me figure out which muscles to work, I definitely was more aware of my body and trying to put in my full effort because it would show up on the screen." Moreover, to assess the usability of the two core features of motion tracking and muscle visualization, the post-questionnaire asked participants to rate their accuracy and responsiveness and obtained comparable results. The score for motion tracking was 3.89 (SD=1.27), and for muscle visualization was 3.67 (SD=0.87)

VR Evaluation: 6DoF motion data from the VR headset helped the VR rehabilitation simulator reconstruct the first-person perspective of participants in the VR environment with the motion trajectory of the VR camera and target line of sight. This data also contributed to the attentional analysis. Seven participants focused more on the streaming patient avatar in the motion-only condition. P5 claimed, "The motion tracking was very helpful to understand if I was performing the movement correctly." P2 also affirmed its functionality: "I used the motion tracking avatar as a validation of my pose, similar to how I used the mirror in real life." However, in the motion simulation and muscle engagement visualization condition, the attention was distributed that four participants focused more on the streaming avatar, three on the muscle panel, and two on the therapist avatar (P10 data not well captured). The scattered attention indicated participants were receiving more meaningful information under the condition.

Specifically, seven participants expressed a positive opinion of the muscle visualization feature. P5 said:" The muscle visualization helped to understand if I was tackling the correct muscles or if there was the need to adjust the movement to tackle the right muscles. "P2 believed that muscle visualization helped him rectify his movements: "For the ones that I knew which muscles I should activate, I would also adjust my pose according to the muscle visualization." Moreover, unlike most participants, P4 focused on the therapist avatar and stated: "...(it) helped remind me how to do exercises I was unfamiliar with." P2 and P8, both rehabilitation newcomers, also praised the educational significance of the therapist reference.

In general, participants valued the overall usability (4.25, SD=0.66), immersion (4.13, SD=1.16), and not causing distraction (1.875 (a value tending to 1 indicates not distractive), SD= 0.78) of the VR rehabilitation simulator. However, some participants also suggested the symptoms of motion sickness and dizziness after wearing the VR headset for 90 minutes.

Iterative Advice: Participants gave many iterative suggestions in qualitative research. Three participants mentioned incorporating more specific motion evaluation, rectification, and instant coaching features. For example, P6 wanted more pre-training: "This feels like an entertaining and useful tool - it would be nice to have some sort of tutorial or help teach a person how to activate their muscles gradually." P2 said: "I wish that the system could suggest whether my posture was different from the gold standard therapist avatar (i.e., rate my performance) so that I better understand whether my posture was correct." P9 suggested that to reduce the recurrence of incorrect exercises, the VR interface should prompt the user to redo and allow more time for learning and adjustment when errors occur. P3 identified audio guidance as an effective communication medium for notice of corrections.

Multiple participants highlighted the requirement for a customized avatar with more sense of identity awareness and psychological adaptation to a persona with matched gender and appearance features. For example, P3 suggested that the VR rehabilitation simulator could improve the avatar design in two ways: "... (I) would like to see the female body when I do the user research. Moreover, in order to more clearly map the details of human movement, she believed that "it might be better to use an avatar with skin rather than muscular man to perform the posture." To prevent introducing variables of individualization, this user research did not introduce custom avatars and other rendering modes. However, future iterations are planned to implement physiologically adaptive or engaging avatar designs and test more rendering display modes than the muscular style.

Moreover, participants proposed implementing the simulator on other display platforms, such as AR (3D), semi-immersive environments (2.5D ring screens), or traditional 2D screens. However, all participants agreed that 3D displays provided a sense of immersion and identity that remained of scientific underpinning and informational significance. For example, the 3D environment allows the user to capture comprehensive perspectives more clearly, and P2 expressed that "... (I want to) change the angle from which I view my current pose. In this way, I could view myself from any angle I want, especially from the back." In response to considerations of other alternative platforms, the thesis reviewed and discussed the advantages and disadvantages of these the mentioned medium in the Discussion Section.

5 Study 2

5.1 Study Design

High-quality remote assessments and adaptive exercise prescriptions from a professional physical therapist are instrumental requirements for a valid at-home rehabilitation. Thus, this user research evaluated the VR rehabilitation simulator on how it empowered post-rehabilitation assessment and improved remote diagnosis comparable to the on-site evaluation. Specifically, it focused on investigating whether offering physical therapists the VR interface with augmented feedback of motion simulation and muscle engagement visualization led to a closer alignment with in-clinic diagnosis.

Study 2 recruited six professional physical therapists specializing in lower extremity rehabilitation diagnosis, including 2 females and 4 males, and an additional therapist involved in the on-site diagnosis. All therapists were between the ages of 27-32 years (M=29.8, SD=2.17) and had been practicing for five years or more. The on-site therapists were involved in the entire process of Study 1, which lasted 12 hours. Other therapists contributed 3 hours to conduct the remote rehabilitation analysis.

As with Study 1, Study 2 required the therapists to evaluate the quality of exercise execution of each participant remotely regarding the two conditions, the motion-only condition and the motion simulation and muscle engagement visualization condition. The order of evaluation for the two conditions was randomized to avoid interference from sequential variables. For each condition, the therapists were provided with the corresponding evidence for the in-depth measurement, including screen recordings of the VR interfaces while participants performed each corresponding therapeutic exercise and on-site filming from the front viewpoint. In traditional assessment methods, therapists have been accustomed to obtaining information through in-field filming. Therefore, the provided screen recordings of the VR rehabilitation simulator were augmentation rather than a complete replacement of the traditional measure.

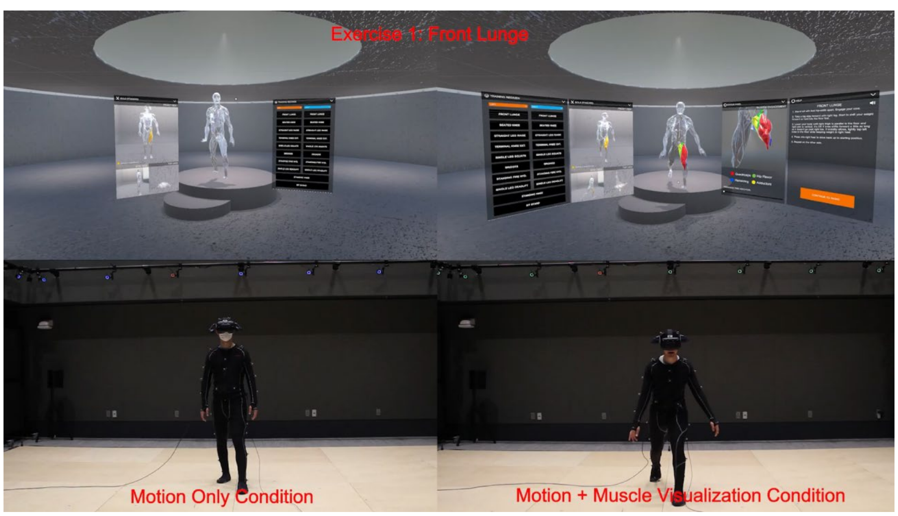

Figure 11 The VR Rehabilitation Simulator Screen Recording and On-Site Filming

Procedure: Study 2 was divided into two parts, including an on-site rehabilitation analysis that served as the ground truth and a diagnostic validation and a post-rehabilitation study conducted by six remote therapists.

(1) **Baseline evaluation:** In-clinic diagnosis typically verifies muscle participation by touching the muscular state, but considering that this may cause masking interference to the motion capture system and increase the noise in the EIT input. Therefore, Study 2 employed an observation-based diagnostic method (likewise frequently used) instead of direct contact with participants. The therapist recognized that the observation-based field analysis was feasible and equally effective. Accordingly, an on-site therapist was recruited to monitor the exercise execution performance of each participant in Study 1 in silence. To prevent the therapist from being distracted by the experimental purpose, she was not informed of any condition determination when each exercise was performed. The therapist's task was to rate the accuracy of muscle engagement involved in each exercise on a 5-point Likert Scale and report the types of misused muscles.

(2) **Post-rehabilitation evaluation:** Study 2 presented six remote participating therapists with multiple input evidence for post-evaluation. The input material for each participant included (1) on-site filming of five motion-only conditioned exercises and five motion simulation and muscle engagement visualization conditioned exercises, and (2) VR screen recordings of the corresponding conditions. The order of the remote evaluation was consistent with the sequence of exercise execution in Study 1, both following the 2x2 within-subjects design. It took 2.5-3 hours for the remote therapist to review the materials and fill out questionnaires. Similar to the on-site assessment, they reported information including scoring, the correct muscle engagement for each exercise, and the incorrectly triggered muscle groups.

5.2 Study Results

The on-site evaluation reported a score of 8.31 (SD=0.70) for the motion-only condition and 8.75 (SD=0.52) for the motion simulation and muscle engagement visualization condition. Study 2 calculated the squared deviation between the ground truth and the scores delivered by the remote physical therapists in both conditions. As shown in Table 3, the average deviation between remote PT and on-site PT was 1.62 (SD=1.27) in the motion-only condition, much higher than the 0.83 (SD=0.58) in the enhanced condition. The difference between these two samples was statistically significant with a 90% confidence level (p-value=0.097). The improvement was more pronounced for several anterior lower limb exercises (e.g., Front Lunge, Single Leg Squats, Terminal Knee Extension) (2.3, SD=1.13), which could potentially be attributed to the fact that the video views provided by Study 2 are all frontal views, making it more straightforward to observe these movements. Multiple therapists suggested that providing multiple views of the screen recordings would help them observe postural and muscular states from different angles, further improving the accuracy of expert advice.

Exercise Type	Motion Only	Motion + Muscle Vis.
Front Lunge	1.36	0.44
Standing Knee Bend	0.82	0.33
Seated Knee	0.13	0.69
Single Leg Deadlift	1.34	1.61
Straight Leg Raise Side	2.69	1.98
Terminal Knee Extension	2.45	0.16
Single Leg Squat	4.25	0.56
Sit to Stand	0.74	1.11
Standing Fire Hydrant	2.06	0.89
Single Leg Bridge	0.35	0.55

Table 3 Rating Devition between On-Site Evaluation and Remote PT Evaluation [12]

Moreover, the remote therapists evaluated the accuracy and responsiveness of the motion tracking and muscle visualization on the 5-point Likert Scale. The score for the motion tracking system averaged 4.4 (SD=0.55), and that for muscle visualization averaged 3.8 (0.45). All participating physical therapists were more satisfied with the rehabilitation assessment in the motion simulation and muscle engagement visualization condition because the additional dimension facilitated the reliability of the assessment and helped them to deliver more accurate feedback to the patient. PT3 said: "[...] makes it so much easier to explain to patients when visual data supports it." In addition, multiple therapists have suggested that the VR rehabilitation simulator could incorporate more gamification elements (i.e., bonus and penalty) as exercise P5 suggested that "[it] will motivate the patients to exercise more frequently and keep them on track of their remote program. "

6 Discussion

In traditional physical space design, designers considered environmental factors, such as geometric aesthetic, spatial dimension, circulation, zoning, materials, and lighting, beyond the customized subjective experience because “brick and mortar” cannot synchronize personalized perception with the physical boundary of interaction. Virtual Reality (VR) technology breaks the limits by simulating and adapting the virtual environment with human-driven feedback. In particular, the VR rehabilitation space satisfied people and achieved rehabilitation goals with self-awareness and environmental responsiveness through enhanced sensing technology, interaction methods, and virtual visualization. This section discussed the aesthetic of selecting technological alternatives to extend the possibilities of the VR rehabilitation simulator to a broader rehabilitation scenario, such as motor learning, upper-limb rehabilitation.

6.1 Virtual Display Medium Alternatives

The VR rehabilitation simulator opted for Virtual Reality technology as the output medium for various reasons, such as reducing noise interference from the physical environment, taking advantage of immersive empathetic simulation, and hardware ubiquity. The thesis also envisioned future research to apply similar sensing techniques, interaction methods, and augmented feedback to the AR setup. Since the two mediums share similar properties, I hypothesize that AR-based rehabilitation-assisted therapy can achieve enhanced training execution and post-assessment in analogy to VR systems. To provide future researchers with additional considerations on selecting mediums within the field of rehabilitation, this thesis discusses the range of scenario-based implementations of other complementary reality platforms, covering their advantages and disadvantages.

Augmented Reality: While the prototypes and experiments presented in this thesis focus on lower extremity rehabilitation and full-body motion capture, more scenarios in the field of remote rehabilitation encourage the convenience of AR's hybrid display properties. In contrast to the computer-simulated 3D environments created by VR, AR focuses on virtual event experiences based on real environments overlaid with visual augmentation. If a spectrum of virtual to real worlds were created, AR's value proposition would be closer to the latter, as the placement coordinates of virtual experiences are based on the spatial matrix conversion of real displays. Therefore, the advantages of AR are more evident in scenarios involving hands-on interaction with real environments such as medical research and surgical training, precision instrument manufacturing and repair, assisted posture correction, and remote rehabilitation robot control. For example, in upper extremity rehabilitation, such as arm and finger therapeutic training, patients usually perform therapeutic exercises on the desktop. The controlled desktop environment allows AR to introduce less real-world visual noise. Thus, the advantages of AR are exploited as it can superimpose virtual visualization information, such as limb mapping, muscle visualization, etc., directly on the real human musculoskeletal without any intervention. In this case, the augmented feedback of one-to-one mapping allows a more intuitive presentation of knowledge of result (KR) and knowledge of performance (KP) [97]. Thus, in the upper limb rehabilitation scenario, this superimposed display will be more immersive than the mirrored virtual image implemented in VR, helping patients visualize and correct training behaviors. Moreover, motor learning is another potential application direction.

However, AR devices still suffer from many application limitations. For example, in terms of imaging technology, the dominant method of Stereoscopic 3D in AR has failed to avoid the vertigo symptoms typically associated with near-eye imaging devices. Another more advanced light field display technology is also limited by the display challenges of hardware size, sampling resolution, and accommodation-vergence matching (VAC). Moreover, the maximum viewing angle range does not exceed 53° (Hololens 2: a horizontal FoV of 43° and a vertical of 29° [98]). Compared to the 210° VR perspective records[99] (HTC VIVE Pro 2 has a 120° Horizontal FoV and 97° vertical [90]), the 3D canvas on which AR can carry information is more limited. Therefore, when designing a virtual rehabilitation display system based on AR, designers can no longer use large-scale all-in-one panels to present information but have to decentralize and condense the virtual interface into prompted UI commands. Another issue that requires additional consideration is the variable of lighting and duration of use. Existing technologies have difficulty rendering AR with clear boundaries, and timing can blur the edges of AR images due to ambient light. Setting the brightness of AR to make the image more integrated with the surrounding environment presented challenges. If the overall light transmission rate of AR glasses is reduced, it will not only reduce the brightness of AR but also the surrounding environment will look darker, which will decrease the quality of feedback harvested from patients during the movement.

Semi-immersive VR (SIVR): Semi-immersive virtual reality is a hybrid medium between VR and physical environments, usually consisting of a high-resolution concaved screen, a projection system, and monitoring sensors. Depending on the use scenario, researchers also introduced multimodal feedback systems, such as assistive rehabilitation robots and touchable control interfaces (yoke, joystick, steering wheel, lever, etc.) for rehabilitation cases. Unlike mixed reality (MR) and traditional head-mounted VR devices, the imaging technology of semi-immersive VR does not rely on any built-in optics within the headset, nor does it require the patient to wear a display device during movement. However, it enables the simulation of a hybrid experience by projecting a geometric distribution in real space (e.g., rings, cave-like). This setup allows SIVR to combine the advantages of immersion, no vertigo, no burden, and natural interaction. However, semi-immersive VR setups involve complex hardware and software components and expensive costs. Usually, they need to be equipped with multiple projection channels or ring screens that are seamlessly stitched together into one giant projection spread to form a high-resolution 2D or 3D stereoscopic image. The setup will be more challenging for full-body motion tracking and rehabilitation scenario (i.e., lower limb rehabilitation) where the requirement for the display area should cover a human height. Potential application scenarios are desktop-based upper extremity rehabilitation or commercial rather than personal services. For example, a rehabilitation hospital can equip multiple SIVR-based self-service rehabilitation systems as a semi-public shared facility.

Non-immersive: Non-immersive displays refer to the screen displays (for smaller area display requirements) or projection displays (for larger area display requirements) that people use most often in their daily lives. The most significant advantage of this approach is its accessibility and flexibility, making it a minimum viable medium to spread among therapists and patients.

6.2 OptiTrack VS. Commercial Tracking Systems

Because the user research in this thesis requires reference to precise motion, the VR rehabilitation simulator adopted OptiTrack, a high-resolution, high-framerate, cinematic-grade optical motion capture system. However, this expensive and space-demanding setup cannot be popularized in home environments. Therefore, the thesis described the measures of using Kinect and Kinect for Windows SDK 2.0 as low-cost alternatives. Another hardware choice for low-cost motion tracking is the integrated desktop trinocular motion capture camera using OptiTrack. According to official data, this consumer-grade solution is equipped with OptiTrack's image processing chip, which supports 120fps motion sampling based on Filter Switch (FS) technology and enables 6DoF sampling and recording of the joint motor [100]. In addition to full-body tracking devices, Leap Motion, a desktop-based compact sensing device that supports naked hand input, is also available for development [57]. Leap Motion's expertise in gesture recognition can form a complementary measure with devices such as Kinect, mainly addressing the needs of upper limb rehabilitation scenarios. Other sensors, such as HTC Vive Tracker 3.0 [101], Vive Wrist Tracker [102], etc., can be placed on joint parts to achieve feasible tracking of extremities.

6.3 Wearable Design with EIT Sensing Technology

The wearable EIT device in this work consisted of a plug-and-play open source EIT sensing board, 32 medical-grade electrodes, and a strap-on leg band. To ensure that the electrodes were evenly distributed and not displaced to provide the most accurate sensing data, the thesis did not implement an integrated electrode strap, but rather disposable ECG electrodes that were individually assembled and distributed. However, it is not convenient to change electrodes frequently in home scenarios. Therefore, future research should consider more integrated input systems and robust assemblies, such as clickable electrodes, or integrating electrode designs into wearable textiles to allow reuse and rapid donning by the users. The more convenient EIT sensing wearables would further allow researchers to use multiple EIT devices for overall muscle testing of the whole body.

7 Conclusion

In conclusion, the main contributions of this paper are：

(1) A VR rehabilitation simulator that integrates two-dimensional input sensing technologies, based on Electrical Impedance Tomography (EIT) and Optical motion tracking system, and a virtual interface with augmented and adaptive visualization deliveries.

(2) A controlled study with ten participants that researched and verified the overall usability and capabilities of the VR simulator in improving the therapeutic exercise execution accuracy during unsupervised physical rehabilitation (compared with traditional measure).

(3) An evaluation study with six physical therapists that proved the VR simulator to facilitate post-rehabilitation assessments.

(4) Alternative technologies that extended the future application areas and made the system more accessible.

Bibliography

1. Weinbaum, S. G. (2016). *Pygmalion's Spectacles*. Simon and Schuster.

2. World Health Organization. (2021, November 10). *Rehabilitation*. https://www.who.int/news-room/fact-sheets/detail/rehabilitation

3. World Health Organization. (2017). *The need to scale up rehabilitation* (WHO/NMH/NVI/17.1). World Health Organization. https://apps.who.int/iris/handle/10665/331210

4. Sveistrup, H. (2004). Motor rehabilitation using virtual reality. *Journal of NeuroEngineering and Rehabilitation*, *1*(1), 10. https://doi.org/10.1186/1743-0003-1-10

5. Malouin, F., Richards, C. L., McFadyen, B., & Doyon, J. (2003). New perspectives of locomotor rehabilitation after stroke. *Medecine sciences*, *19*(10), 994–998. https://doi.org/10.1051/medsci/20031910994

6. Alimanova, M., Borambayeva, S., Kozhamzharova, D., Kurmangaiyeva, N., Ospanova, D., Tyulepberdinova, G., Gaziz, G., & Kassenkhan, A. (2017). Gamification of Hand Rehabilitation Process Using Virtual Reality Tools: Using Leap Motion for Hand Rehabilitation. *2017 First IEEE International Conference on Robotic Computing (IRC)*, 336–339. https://doi.org/10.1109/IRC.2017.76

7. Khademi, M., Mousavi Hondori, H., McKenzie, A., Dodakian, L., Lopes, C. V., & Cramer, S. C. (2014). Free-hand interaction with leap motion controller for stroke rehabilitation. *CHI '14 Extended Abstracts on Human Factors in Computing Systems*, 1663–1668. https://doi.org/10.1145/2559206.2581203

8. Kytö, M., Maye, L., & McGookin, D. (2019). Using Both Hands: Tangibles for Stroke Rehabilitation in the Home. *Proceedings of the 2019 CHI Conference on Human Factors*

in Computing Systems, 1–14. https://doi.org/10.1145/3290605.3300612

9. *Ring Fit Adventure*. (n.d.). Retrieved May 13, 2022, from https://ringfitadventure.nintendo.com/

10. Omrani, M., Kaufman, M. T., Hatsopoulos, N. G., & Cheney, P. D. (2017). Perspectives on classical controversies about the motor cortex. *Journal of Neurophysiology*, *118*(3), 1828–1848. https://doi.org/10.1152/jn.00795.2016

11. Bestsennyy, O., Gilbert, G., Harris, A., & Rost, J. (n.d.). *Telehealth: A quarter-trillion- dollar post-COVID-19 reality?* 10.

12. Zhu, J., Lei, Y., Shah, A., R. Schein, G., Ghaednia, H., H. Schwab, J., Harteveld, C., & Mueller, S. (n.d.). MuscleVR: Improving Unsupervised Physical Rehabilitation by Monitoring and Visualizing Muscle Engagement. . . *In Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology (UIST '22). ACM.*

13. Roos, E. M., Roos, H. P., Lohmander, L. S., Ekdahl, C., & Beynnon, B. D. (1998). Knee Injury and Osteoarthritis Outcome Score (KOOS)—Development of a Self-Administered Outcome Measure. *Journal of Orthopaedic & Sports Physical Therapy*, *28*(2), 88–96. https://doi.org/10.2519/jospt.1998.28.2.88

14. Binkley, J. M., Stratford, P. W., Lott, S. A., & Riddle, D. L. (1999). The Lower Extremity Functional Scale (LEFS): Scale Development, Measurement Properties, and Clinical Application. *Physical Therapy*, *79*(4), 371–383. https://doi.org/10.1093/ptj/79.4.371

15. Zhang, H. (2017). Head-mounted display-based intuitive virtual reality training system for the mining industry. *International Journal of Mining Science and Technology*, *27*(4), 717–722. https://doi.org/10.1016/j.ijmst.2017.05.005

16. Gallo, L., Minutolo, A., & De Pietro, G. (2010). A user interface for VR-ready 3D medical imaging by off-the-shelf input devices. *Computers in Biology and Medicine*, *40*(3), 350–

358. https://doi.org/10.1016/j.compbiomed.2010.01.006

17. Burdea, G. C. (2003). Virtual Rehabilitation – Benefits and Challenges. *Methods of Information in Medicine*, *42*(5), 519–523. https://doi.org/10.1055/s-0038-1634378

18. Satava, R. M. (1995). Virtual Reality, Telesurgery, and the New World Order of Medicine. *Journal of Image Guided Surgery*, *1*(1), 12–16. https://doi.org/10.3109/10929089509106821

19. Spiegel, B. (n.d.). *Virtual Reality and the COVID Mental Health Crisis*. Scientific American. Retrieved May 13, 2022, from https://www.scientificamerican.com/article/virtual-reality-and-the-covid-mental-health-crisis/

20. Saposnik, G. (2016). Virtual Reality in Stroke Rehabilitation. In B. Ovbiagele (Ed.), *Ischemic Stroke Therapeutics: A Comprehensive Guide* (pp. 225–233). Springer International Publishing. https://doi.org/10.1007/978-3-319-17750-2_22

21. Maggio, M. G., De Luca, R., Molonia, F., Porcari, B., Destro, M., Casella, C., Salvati, R., Bramanti, P., & Calabro, R. S. (2019). Cognitive rehabilitation in patients with traumatic brain injury: A narrative review on the emerging use of virtual reality. *Journal of Clinical Neuroscience*, *61*, 1–4. https://doi.org/10.1016/j.jocn.2018.12.020

22. de Araújo, A. V. L., Neiva, J. F. de O., Monteiro, C. B. de M., & Magalhães, F. H. (2019). Efficacy of Virtual Reality Rehabilitation after Spinal Cord Injury: A Systematic Review. *BioMed Research International*, *2019*, e7106951. https://doi.org/10.1155/2019/7106951

23. Levin, M. F., Weiss, P. L., & Keshner, E. A. (2015). Emergence of Virtual Reality as a Tool for Upper Limb Rehabilitation: Incorporation of Motor Control and Motor Learning Principles. *Physical Therapy*, *95*(3), 415–425. https://doi.org/10.2522/ptj.20130579

24. Chau, T., Eaton, C., Lamont, A., Schwellnus, H., & Tam, C. (2006). Augmented environments

for pediatric rehabilitation. *Technology and Disability*, *18*(4), 167–171. https://doi.org/10.3233/TAD-2006-18402

25. *DIEGO®: The bilateral Arm-Shoulder-Therapysystem*. (n.d.). Tyromotion. Retrieved May 13, 2022, from https://tyromotion.com/en/products/diego/

26. Nissler, C., Nowak, M., Connan, M., Büttner, S., Vogel, J., Kossyk, I., Márton, Z.-C., & Castellini, C. (2019). VITA—an everyday virtual reality setup for prosthetics and upper-limb rehabilitation. *Journal of Neural Engineering*, *16*(2), 026039. https://doi.org/10.1088/1741-2552/aaf35f

27. Brütsch, K., Schuler, T., Koenig, A., Zimmerli, L., (-Koeneke), S. M., Lünenburger, L., Riener, R., Jäncke, L., & Meyer-Heim, A. (2010). Influence of virtual reality soccer game on walking performance in robotic assisted gait training for children. *Journal of NeuroEngineering and Rehabilitation*, *7*(1), 15. https://doi.org/10.1186/1743-0003-7-15

28. Wrzesien, M., Burkhardt, J.-M., Alcañiz Raya, M., & Botella, C. (2011). Mixing psychology and HCI in evaluation of augmented reality mental health technology. *CHI '11 Extended Abstracts on Human Factors in Computing Systems*, 2119–2124. https://doi.org/10.1145/1979742.1979898

29. Horigome, T., Kurokawa, S., Sawada, K., Kudo, S., Shiga, K., Mimura, M., & Kishimoto, T. (2020). Virtual reality exposure therapy for social anxiety disorder: A systematic review and meta-analysis. *Psychological Medicine*, *50*(15), 2487–2497. https://doi.org/10.1017/S0033291720003785

30. Parsons, T. D., Rizzo, A. A., Rogers, S., & York, P. (2009). Virtual reality in paediatric rehabilitation: A review. *Developmental Neurorehabilitation*, *12*(4), 224–238. https://doi.org/10.1080/17518420902991719

31. Evans, H., Lakshmi, U., Watson, H., Ismail, A., Sherrill, A. M., Kumar, N., & Arriaga, R. I. (2020). Understanding the Care Ecologies of Veterans with PTSD. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (pp. 1–15). Association for Computing Machinery. https://doi.org/10.1145/3313831.3376170

32. *Vivid Vision*. (n.d.). Vivid Vision. Retrieved May 13, 2022, from https://www.seevividly.com/

33. Gromala, D., Tong, X., Choo, A., Karamnejad, M., & Shaw, C. D. (2015). The Virtual Meditative Walk: Virtual Reality Therapy for Chronic Pain Management. *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, 521–524. https://doi.org/10.1145/2702123.2702344

34. Hoffman, H. G., Patterson, D. R., & Carrougher, G. J. (2000). Use of Virtual Reality for Adjunctive Treatment of Adult Burn Pain During Physical Therapy: A Controlled Study. *The Clinical Journal of Pain*, *16*(3), 244–250. https://journals.lww.com/clinicalpain/Fulltext/2000/09000/Use_of_Virtual_Reality_for_Adjunctive_Treatment_of.10.aspx?casa_token=ost8YqllqE8AAAAA:SpcX_N6DIwVgYSDXXo0NVfGxJTBcA64nhOOj7ASPiSA5ABeCUR9Q6KSu_yeR4d3gnTJZvhNM94ClUv0LSd-e0iQ

35. Da Col, T., Caccianiga, G., Catellani, M., Mariani, A., Ferro, M., Cordima, G., De Momi, E., Ferrigno, G., & de Cobelli, O. (2021). Automating Endoscope Motion in Robotic Surgery: A Usability Study on da Vinci-Assisted Ex Vivo Neobladder Reconstruction. *Frontiers in Robotics and AI*, *8*. https://www.frontiersin.org/article/10.3389/frobt.2021.707704

36. Gasques, D., Johnson, J. G., Sharkey, T., Feng, Y., Wang, R., Xu, Z. R., Zavala, E., Zhang, Y., Xie, W., Zhang, X., Davis, K., Yip, M., & Weibel, N. (2021). ARTEMIS: A Collaborative Mixed-Reality System for Immersive Surgical Telementoring. *Proceedings of the 2021*

CHI Conference on Human Factors in Computing Systems, 1–14. https://doi.org/10.1145/3411764.3445576

37. Mubin, O., Alnajjar, F., Jishtu, N., Alsinglawi, B., & Mahmud, A. A. (2019). Exoskeletons With Virtual Reality, Augmented Reality, and Gamification for Stroke Patients' Rehabilitation: Systematic Review. *JMIR Rehabilitation and Assistive Technologies*, *6*(2), e12010. https://doi.org/10.2196/12010
38. Klamroth-Marganska, V., Blanco, J., Campen, K., Curt, A., Dietz, V., Ettlin, T., Felder, M., Fellinghauer, B., Guidali, M., Kollmar, A., Luft, A., Nef, T., Schuster-Amft, C., Stahel, W., & Riener, R. (2014). Three-dimensional, task-specific robot therapy of the arm after stroke: A multicentre, parallel-group randomised trial. *The Lancet Neurology*, *13*(2), 159–166. https://doi.org/10.1016/S1474-4422(13)70305-3
39. Khor, K. X., Chin, P. J. H., Yeong, C. F., Su, E. L. M., Narayanan, A. L. T., Abdul Rahman, H., & Khan, Q. I. (2017). Portable and Reconfigurable Wrist Robot Improves Hand Function for Post-Stroke Subjects. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *25*(10), 1864–1873. https://doi.org/10.1109/TNSRE.2017.2692520
40. Hymes, K., Hammer, J., Seyalioglu, H., Dow-Richards, C., Brown, D., Hambridge, T., Ventrice, J., Baker, M., Kim, Y. J., Hutchings, T., & Evans, W. S. (2021). Designing Game-Based Rehabilitation Experiences for People with Aphasia. *Proceedings of the ACM on Human-Computer Interaction*, *5*(CHI PLAY), 270:1-270:31. https://doi.org/10.1145/3474697
41. Arpaia, P., De Benedetto, E., Dodaro, C. A., Duraccio, L., & Servillo, G. (2021). Metrology-Based Design of a Wearable Augmented Reality System for Monitoring Patient's Vitals in

Real Time. *IEEE Sensors Journal*, *21*(9), 11176–11183. https://doi.org/10.1109/JSEN.2021.3059636

42. Budde, V., Reichling, J., & Kraetsch, C. (2019). *Requirement analysis for an AR-based teleconsultation system*. https://doi.org/10.18420/muc2019-ws-634
43. Zhu, E., Hadadgar, A., Masiello, I., & Zary, N. (2014). Augmented reality in healthcare education: An integrative review. *PeerJ*, *2*, e469. https://doi.org/10.7717/peerj.469
44. Alamri, A., Cha, J., & El Saddik, A. (2010). AR-REHAB: An Augmented Reality Framework for Poststroke-Patient Rehabilitation. *IEEE Transactions on Instrumentation and Measurement*, *59*(10), 2554–2563. https://doi.org/10.1109/TIM.2010.2057750
45. Sousa, M., Vieira, J., Medeiros, D., Arsenio, A., & Jorge, J. (2016). SleeveAR: Augmented Reality for Rehabilitation using Realtime Feedback. *Proceedings of the 21st International Conference on Intelligent User Interfaces*, 175–185. https://doi.org/10.1145/2856767.2856773
46. Sigrist, R., Rauter, G., Riener, R., & Wolf, P. (2013). Augmented visual, auditory, haptic, and multimodal feedback in motor learning: A review. *Psychonomic Bulletin & Review*, *20*(1), 21–53. https://doi.org/10.3758/s13423-012-0333-8
47. Da Gama, A. E. F., Chaves, T. M., Figueiredo, L. S., Baltar, A., Meng, M., Navab, N., Teichrieb, V., & Fallavollita, P. (2016). MirrARbilitation: A clinically-related gesture recognition interactive tool for an AR rehabilitation system. *Computer Methods and Programs in Biomedicine*, *135*, 105–114. https://doi.org/10.1016/j.cmpb.2016.07.014
48. Luo, X., Kline, T., Fischer, H. C., Stubblefield, K. A., Kenyon, R. V., & Kamper, D. G. (2005). Integration of Augmented Reality and Assistive Devices for Post-Stroke Hand Opening Rehabilitation. *2005 IEEE Engineering in Medicine and Biology 27th Annual Conference*,

6855–6858. https://doi.org/10.1109/IEMBS.2005.1616080

49. Jaffe, D. L., Brown, D. A., Pierson-Carey, C. D., Buckley, E. L., & Lew, H. L. (2004). Stepping over obstacles to improve walking in individuals with poststroke hemiplegia. *The Journal of Rehabilitation Research and Development*, *41*(3A), 283. https://doi.org/10.1682/JRRD.2004.03.0283

50. Burke, J. W., McNeill, M. D. J., Charles, D. K., Morrow, P. J., Crosbie, J. H., & McDonough, S. M. (2010). Augmented Reality Games for Upper-Limb Stroke Rehabilitation. *2010 Second International Conference on Games and Virtual Worlds for Serious Applications*, 75–78. https://doi.org/10.1109/VS-GAMES.2010.21

51. Mumford, N., Duckworth, J., Thomas, P. R., Shum, D., Williams, G., & Wilson, P. H. (2012). Upper-limb virtual rehabilitation for traumatic brain injury: A preliminary within-group evaluation of the elements system. *Brain Injury*, *26*(2), 166–176. https://doi.org/10.3109/02699052.2011.648706

52. Jakus, G., Stojmenova, K., Tomažič, S., & Sodnik, J. (2017). A system for efficient motor learning using multimodal augmented feedback. *Multimedia Tools and Applications*, *76*(20), 20409–20421. https://doi.org/10.1007/s11042-016-3774-7

53. Khademi, M. (2014). Comparing direct and indirect interaction in stroke rehabilitation. *CHI '14 Extended Abstracts on Human Factors in Computing Systems*, 1639–1644. https://doi.org/10.1145/2559206.2581192

54. Chang, Y.-J., Chen, S.-F., & Huang, J.-D. (2011). A Kinect-based system for physical rehabilitation: A pilot study for young adults with motor disabilities. *Research in Developmental Disabilities*, *32*(6), 2566–2570. https://doi.org/10.1016/j.ridd.2011.07.002

55. *Evolv Rehabilitation Technologies*. (n.d.). Retrieved May 13, 2022, from

https://evolvrehab.com/

56. Fernández-González, P., Carratalá-Tejada, M., Monge-Pereira, E., Collado-Vázquez, S., Sánchez-Herrera Baeza, P., Cuesta-Gómez, A., Oña-Simbaña, E. D., Jardón-Huete, A., Molina-Rueda, F., Balaguer-Bernaldo de Quirós, C., Miangolarra-Page, J. C., & Cano-de la Cuerda, R. (2019). Leap motion controlled video game-based therapy for upper limb rehabilitation in patients with Parkinson's disease: A feasibility study. *Journal of NeuroEngineering and Rehabilitation*, *16*(1), 133. https://doi.org/10.1186/s12984-019-0593-x

57. Wang, Z., Wang, P., Xing, L., Mei, L., Zhao, J., & Zhang, T. (2017). Leap Motion-based virtual reality training for improving motor functional recovery of upper limbs and neural reorganization in subacute stroke patients. *Neural Regeneration Research*, *12*(11), 1823–1831. https://doi.org/10.4103/1673-5374.219043

58. Pani, D., Barabino, G., Dessì, A., Tradori, I., Piga, M., Mathieu, A., & Raffo, L. (2014). A Device for Local or Remote Monitoring of Hand Rehabilitation Sessions for Rheumatic Patients. *IEEE Journal of Translational Engineering in Health and Medicine*, *2*, 1–11. https://doi.org/10.1109/JTEHM.2014.2299274

59. Henriksson, M., & Fransson, M. (2018). *Force-Sensing Rehabilitation Glove: A tool to facilitate rehabilitation of reduced hand strength*. http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-254287

60. Khurelbaatar, T., Kim, K., Lee, S., & Kim, Y. H. (2015). Consistent accuracy in whole-body joint kinetics during gait using wearable inertial motion sensors and in-shoe pressure sensors. *Gait & Posture*, *42*(1), 65–69. https://doi.org/10.1016/j.gaitpost.2015.04.007

61. Krishnan, V., Khoo, I., Marayong, P., DeMars, K., & Cormack, J. (2016). Gait Training in

Chronic Stroke Using Walk-Even Feedback Device: A Pilot Study. *Neuroscience Journal*, *2016*, 6808319. https://doi.org/10.1155/2016/6808319

62. Taylor, M., Goubran, R., & Knoefel, F. (2012). Patient standing stability measurements using pressure sensitive floor sensors. *2012 IEEE International Instrumentation and Measurement Technology Conference Proceedings*, 1275–1279. https://doi.org/10.1109/I2MTC.2012.6229355
63. Holden, A., McNaney, R., Balaam, M., Thompson, R., Hammerla, N., Ploetz, T., Jackson, D., Price, C., Brkic, L., & Olivier, P. (2015). CueS: Cueing for upper limb rehabilitation in stroke. *Proceedings of the 2015 British HCI Conference*, 18–25. https://doi.org/10.1145/2783446.2783576
64. Ley-Flores, J., Turmo Vidal, L., Berthouze, N., Singh, A., Bevilacqua, F., & Tajadura-Jiménez, A. (2021). SoniBand: Understanding the Effects of Metaphorical Movement Sonifications on Body Perception and Physical Activity. *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, 1–16. https://doi.org/10.1145/3411764.3445558
65. Patel, S., Park, H., Bonato, P., Chan, L., & Rodgers, M. (2012). A review of wearable sensors and systems with application in rehabilitation. *Journal of NeuroEngineering and Rehabilitation*, *9*(1), 21. https://doi.org/10.1186/1743-0003-9-21
66. Hondori, H., Khademi, M., & Lopes, C. (2012). *Monitoring Intake Gestures using Sensor Fusion (Microsoft Kinect and Inertial Sensors) for Smart Home Tele-Rehab Setting*.
67. Márquez Segura, E., Turmo Vidal, L., Waern, A., Duval, J., Parrilla Bel, L., & Altarriba Bertran, F. (2021). Physical Warm-up Games: Exploring the Potential of Play and Technology Design. *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, 1–14. https://doi.org/10.1145/3411764.3445163

68. Žagar, T., & Križaj, D. (2005). Validation of an accelerometer for determination of muscle belly radial displacement. *Medical and Biological Engineering and Computing*, *43*(1), 78–84. https://doi.org/10.1007/BF02345126

69. Kaczmarek, P., Celichowski, J., Drzymała-Celichowska, H., & Kasiński, A. (2009). The image of motor units architecture in the mechanomyographic signal during the single motor unit contraction: In vivo and simulation study. *Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology*, *19*(4), 553–563. https://doi.org/10.1016/j.jelekin.2008.03.007

70. Rudolph, J. C. R., Holman, D., De Araujo, B., Jota, R., Wigdor, D., & Savage, V. (2022). Sensing Hand Interactions with Everyday Objects by Profiling Wrist Topography. *Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction*, 1–14. https://doi.org/10.1145/3490149.3501320

71. Esposito, D., Andreozzi, E., Fratini, A., Gargiulo, G. D., Savino, S., Niola, V., & Bifulco, P. (2018). A Piezoresistive Sensor to Measure Muscle Contraction and Mechanomyography. *Sensors*, *18*(8), 2553. https://doi.org/10.3390/s18082553

72. Hosono, S., Nishimura, S., Iwasaki, K., & Tamaki, E. (2019). A Method for Estimating the Load on Muscles Using a Wearable IR Sensor Array Device. *Proceedings of the 2019 2nd International Conference on Sensors, Signal and Image Processing*, 77–81. https://doi.org/10.1145/3365245.3365258

73. Zhu, J., Snowden, J. C., Verdejo, J., Chen, E., Zhang, P., Ghaednia, H., Schwab, J. H., & Mueller, S. (2021). EIT-kit: An Electrical Impedance Tomography Toolkit for Health and Motion Sensing. *The 34th Annual ACM Symposium on User Interface Software and Technology*, 400–413. https://doi.org/10.1145/3472749.3474758

74. Zhang, Y., & Harrison, C. (2015). Tomo: Wearable, Low-Cost Electrical Impedance Tomography for Hand Gesture Recognition. *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*, 167–173. https://doi.org/10.1145/2807442.2807480

75. Romsauerova, A., McEwan, A., Horesh, L., Yerworth, R., Bayford, R. H., & Holder, D. S. (2006). Multi-frequency electrical impedance tomography (EIT) of the adult human head: Initial findings in brain tumours, arteriovenous malformations and chronic stroke, development of an analysis method and calibration. *Physiological Measurement*, *27*(5), S147. https://doi.org/10.1088/0967-3334/27/5/S13

76. Adler, A., & Lionheart, W. R. B. (2006). Uses and abuses of EIDORS: An extensible software base for EIT. *Physiological Measurement*, *27*(5), S25–S42. https://doi.org/10.1088/0967-3334/27/5/S03

77. *MathWorks*. (n.d.). Retrieved May 13, 2022, from https://www.mathworks.com/

78. *Open EIT*. (n.d.). GitHub. Retrieved May 13, 2022, from https://github.com/OpenEIT

79. *Teensy® 4.0*. (n.d.). Retrieved May 13, 2022, from https://www.pjrc.com/store/teensy40.html

80. Grychtol, B., Schramel, J. P., Braun, F., Riedel, T., Auer, U., Mosing, M., Braun, C., Waldmann, A. D., Böhm, S. H., & Adler, A. (2019). Thoracic EIT in 3D: Experiences and recommendations. *Physiological Measurement*, *40*(7), 074006. https://doi.org/10.1088/1361-6579/ab291d

81. *OptiTrack*. (n.d.). OptiTrack. Retrieved May 13, 2022, from http://optitrack.com/index.html

82. *Motive*. (n.d.). OptiTrack. Retrieved May 13, 2022, from http://optitrack.com/software/motive/index.html

83. *Motion Capture Markers*. (n.d.). OptiTrack. Retrieved May 13, 2022, from

http://optitrack.com/accessories/markers/index.html

84. *Vicon*. (n.d.). Vicon. Retrieved May 13, 2022, from https://www.vicon.com/

85. *VGB*. (n.d.). Retrieved May 13, 2022, from https://kinect.github.io/tutorial/lab12/index.html

86. grbury. (n.d.). *Start designing and prototyping—Mixed Reality*. Retrieved May 13, 2022, from https://docs.microsoft.com/en-us/windows/mixed-reality/design/design

87. *Designing Screen Interfaces for VR (Google I/O '17)*. (n.d.). Retrieved May 13, 2022, from https://www.youtube.com/watch?v=ES9jArHRFHQ

88. *XR Design Guidelines*. (n.d.). Retrieved May 13, 2022, from https://docs.ultraleap.com/xr-guidelines/

89. Jia, Y. (2020). *Constructing virtual reality exhibitions with multimodal interactions* [Thesis, Massachusetts Institute of Technology]. https://dspace.mit.edu/handle/1721.1/127560

90. *VIVE Pro 2 Specs | VIVE United States*. (n.d.). Retrieved May 16, 2022, from https://www.vive.com/us/product/vive-pro2/specs/

91. *VIVE Pro 2*. (n.d.). Retrieved May 13, 2022, from https://www.vive.com/us/product/vive-pro2/overview/

92. BioDigital. (n.d.). *Interactive 3D Anatomy—Disease Platform*. BioDigital. Retrieved May 13, 2022, from https://www.biodigital.com/?utm_source=google&utm_medium=CPC&utm_campaign=visualization&gclid=Cj0KCQjwg_iTBhDrARIsAD3Ib5gQEuzRzEoSvY-CwNX3sj4olhT4Os-YxkX9u_I0wlBzYvS54MEJT88aAv_pEALw_wcB

93. McNeel. (n.d.). *Rhinoceros 3D*. www.rhino3d.com. Retrieved May 13, 2022, from https://www.rhino3d.com/cn/

94. Blender. (n.d.). Blender.org—Home of the Blender project—Free and Open 3D Creation

Software. *Blender.Org*. Retrieved May 13, 2022, from https://www.blender.org/

95. *Auto-Rig Pro—Blender Market*. (n.d.). Retrieved May 13, 2022, from https://www.blendermarket.com/products/auto-rig-pro

96. Rand, J. A. (1993). *Total Knee Arthroplasty*. Raven Press.

97. Sharma, D. A., Chevidikunnan, M. F., Khan, F. R., & Gaowgzeh, R. A. (2016). Effectiveness of knowledge of result and knowledge of performance in the learning of a skilled motor activity by healthy young adults. *Journal of Physical Therapy Science*, *28*(5), 1482–1486. https://doi.org/10.1589/jpts.28.1482

98. *HoloLens 2's Real Field Of View Revealed—UploadVR*. (2019, February 25). https://uploadvr.com/hololens-2-field-of-view/

99. *StarVR HMD With 210-Degree FOV Is $3,200 For Developers*. (n.d.). Retrieved May 16, 2022, from https://uploadvr.com/starvr-one-3200-developers/

100. *Desktop Motion Capture*. (n.d.). OptiTrack. Retrieved May 16, 2022, from http://optitrack.com/about/press/20110222.html

101. *VIVE Tracker (3.0) | VIVE United States*. (n.d.). Retrieved May 16, 2022, from https://www.vive.com/us/accessory/tracker3/

102. *VIVE Hardware and Software Update*. (2022, January 5). VIVE Blog. https://blog.vive.com/us/2022/01/05/vive-hardware-software-update/