Magic Mirror on the Wall: Reflecting the Realities of Lower Limb Rehabilitation in Virtual Reality

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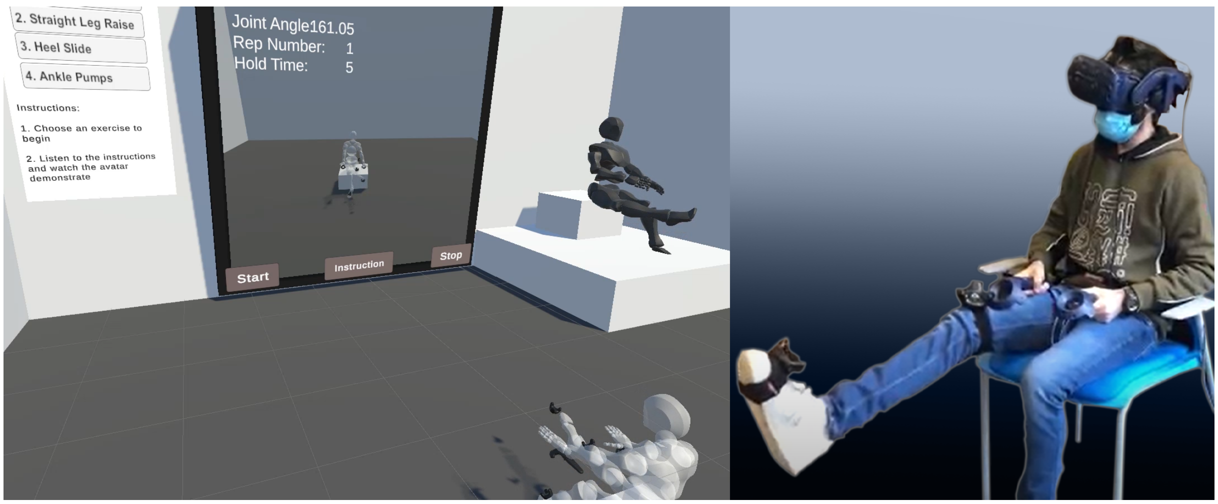

Figure 1: Virtual training environment with mirror and avatar instructor, and participant

ABSTRACT

Virtual reality (VR) could increase access, improve effectiveness, and reduce costs for physical rehabilitation; however, there are open questions regarding the development of VR rehabilitation applications. This work addresses data capture and usability questions by developing and testing a low-cost lower limb rehabilitation system in VR. We present our ongoing work towards the following goals: (1) Achieve accurate data capture of player performance during lower limb rehabilitation in VR, (2) Deliver relevant performance feedback to players in real-time, and (3) Examine system performance and design strategy through usability testing. Our prototype demonstrates a viable framework combining the Unity3D game engine, an inverse kinematics solver, and HTC Vive VR hardware. Using cameraless motion capture to create real-time user feedback, we test six participants examining the strengths and limitations of our prototype for accurate and accessible rehabilitation in VR. We highlight opportunities for development and outline experience design suggestions for future work.

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CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; *Usability testing*; Interaction techniques; • **Applied computing** → Consumer health.

KEYWORDS

Virtual Reality, Virtual Mirror, Motion Capture, Lower Body, Rehabilitation, Inertial Sensors

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1 INTRODUCTION

A patient's prompt and consistent effort in rehabilitation can significantly reduce pain while improving functionality and quality of life; however, the cost and availability of physical therapy are obstacles to access for many patients in need [39]. With the latest technological advances, Virtual Reality (VR) may be able to address such obstacles [16, 35]. Currently, VR is readily available, reasonably affordable, and there are plenty of applications for it; despite this, the practical utility of these applications has been slower to emerge [48]. Physical therapy applications in VR with real-time feedback and guided exercise training have also recently become available [30, 50]. However, rehabilitation for lower limbs is noticeably absent from VR. While the tools to create lower body VR rehabilitation programs exist, the best of these tools have historically either been too complicated to set up or too expensive to justify in the context of home-based rehabilitation. Recent innovations in wearable sensor arrays suggest this history is coming to an end, and research is needed to assemble and test the interrelated factors of design and development for their integration in VR [28]. To this end, we investigate available sensors, hardware, and software tools to develop a lower body rehabilitation in VR using the lowest-cost technologies readily available.

Specifically, in this research, we ask: What is the most accurate, most straightforward, and lowest cost solution to human motion analysis for lower limb rehabilitation in VR? To answer this question and better understand how to create practical utility for patients needing lower body rehabilitation in VR, we base our investigation around the standard first-stage total knee arthroplasty (TKA) rehabilitation protocol and test the system with healthy volunteers. Our research outlines an extensible suite of tools and the design thinking behind implementing these tools to create a lower limb rehabilitation prototype. This prototype illuminates the challenges for constructing VR systems of this kind, as well as what is essential to users and a future path for this work. More importantly, however, our prototype maps a viable strategy for delivering lower limb rehabilitation to patients in VR, by connecting existing hardware and software in the development ecosystem into a testable system.

2 RELATED WORK

Developing VR rehabilitation is complex, multifaceted, interdisciplinary work. Here we limit our focus to the central pillar supporting the development of our prototype: monitoring human movement to deliver rehabilitation training in VR. Our work primarily targets the tracking of physical movement and the monitoring of poses within VR, with the critical secondary interest in the mental needs of patients performing rehabilitation in the medium. This section charts our chosen path towards a non-optical wearable sensor-based motion capture strategy for monitoring human movement and creating feedback for patients in VR.

2.1 Monitoring Human Movement

Rehabilitation traditionally has relied on in-person diagnostics, training, and treatment sessions, and technical solutions for physical therapy cannot easily replicate a therapist's expertise [19]. However, motion capture technologies do have wide adoption and proven utility *assisting* therapists in the diagnoses and tracking of their patients over time. Motion capture technologies have proven value in studying athletic performance and helping athletes avoid injuries and recover from them [5]. VR also tracks users' movements, and therapeutic applications can be derived from the data. Automated real-time rehabilitation applications have been studied using the Microsoft Kinect from technical solutions using rule-based designs [53]. We anticipate further advances in physiotherapy from the opportunities inherent in the combination of motion capture and VR.

Traditionally, state-of-the-art in motion capture technology has come from optical sensors. Companies like *Vicon* [45], *Qualisys* [29] and *PhaseSpace* [17] use combinations of multiple sensors and cameras to achieve highly accurate 3D models of biomechanical motion, and require technical laboratory setups. While marker-less motion capture systems using cameras and computer vision algorithms can reduce much of the complexity in a motion capture system, the costs typically remain high. *Theia* [43] and *The Captury* [42] estimate and generate 3D models of motion from multiple camera perspectives. With or without markers, optical technologies rely on an environmental system looking inwards to understand human motion by using cameras in an "outside-in" approach to finding the body's motion in space. Optical systems for studies of human motion are subject to occlusion, where one part of the body is obscured from view by another and therefore require the synchronization of multiple cameras to ensure accuracy.

"Non-optical" systems, measuring inertial or mechanical movement, record motion data from the "inside-out" relating calibrated tracked points on the body to one another and mapping their changes over time. Well-known systems such as *Xsens* [51], *Perception Neuron* [25], *Motion Shadow* [37], and *Xenoma* [49] use inertial measurement units (IMUs) to develop this kind of inside-out perspective on motion capture. Typically, these systems use around 17 IMUs to create comprehensive full-body tracking solutions. When properly calibrated and synchronized, IMU sensors can capture a subject's movement with similar accuracy to high-end optical systems [41, 44]. Research has investigated custom low-cost single IMU implementations for lower limb rehabilitation in a gamified context [21], as well as the custom development of low-cost IMU sensor arrays [7]. We leverage the IMUs natively available in the HTC Vive Pro VR hardware to approximate the low-cost IMU-based non-optical motion capture that our design strategy requires.

2.2 Human Motion in VR

From visual aesthetics to system responsiveness, users expect digital experiences to be aware of and understand their intentions, not just in service of their actions [22]. For a system to be aware and understanding of human motion in VR, full-body tracking is required. VR rehabilitation applications that support patients with lower limb therapy at home must be robust, low-cost, and lightweight while monitoring human movement with clinical accuracy. In this work, we anticipate a low-cost cameraless full-body tracking future in VR by using the lowest cost system available today, combining the HTC Vive Pro headset [47] with Vive Trackers [46] in Unity3D [40].

Rehabilitation protocols in VR have the potential to enhance patient engagement and boost motivations [26]. The work of Caserman et al. [4, 9, 10] exemplifies an essential attribute for rehabilitation in VR: just tracking the body's motion is not enough; the system must also recognize body positions in real-time and provide feedback to users. Additionally, the work by Elor and Kurniawan [12] provides a contextual framework for our goals, outlining the possibilities for revolutionizing rehabilitation in the medium of VR. Among these possibilities is the potential for VR to address multiple needs simultaneously, designing for both physical and mental health. Rehabilitation is about the body, and in VR presence [36] and immersion [32] affect avatar embodiment [27] and body ownership [33]. This work focuses on supporting a user's sense of ownership and creating presence through controlling the virtual body.

Our efforts are directed by researching these strategies for monitoring human movement to generate detailed and relevant feedback to patients in real-time while balancing tasks with entertainment to relieve monotony and distract from the pain. There are unsolved problems in each dimension of this effort, yet enough partial solutions to begin designing, developing, and testing rehabilitation experiences for the lower body.

3 DESIGN

In our prototype, we follow a *research-through-design* approach [13] to demonstrate the feasibility of an accurate, low-cost solution for human motion analysis for lower limb rehabilitation in VR. Here we describe (1) the exercises in our system, (2) the exercise tracking, (3) the design of the training environment, and (4) our use of sensor data to provide real-time feedback.

3.1 Rehabilitation Protocol

A typical TKA rehabilitation protocol progresses through four stages over 16 weeks. Each stage outlines a set of suggested exercises to be performed three times every day and criteria for evaluating progression from one stage to the next. Our work uses the Total Knee Arthroplasty Protocol developed by Brigham and Women's Hospital Department of Rehabilitation Services [6]. This protocol directs each phase of the rehabilitation with metrics for completion. Our prototype begins with only the first stage exercises of the protocol.

Our prototype delivers the four exercises of the TKA protocol for which our tracker method is applicable. In the first stage of our TKA protocol, there are six exercises, one seated and five laying down: seated long arc quad, quad sets, ankle pumps, straight leg raises, heel slides, and terminal knee extensions. We can monitor only four exercises by moving a patient's limbs: the seated long arc quad, straight leg raises, heel slides, and ankle pumps. The quad sets and the terminal knee extensions are defined primarily by muscle activation rather than limb movement; they do not produce sufficient changes in tracker positions to create strong signals from IMU sensors. This limitation points to the need for a multimodal sensor solution.

3.2 Exercise Tracking

The Vive Tracker is an IMU sensor that can track points in the real world for inclusion in virtual environments. Placed on a user's body, they can be used to support full-body tracking. Function and accuracy can vary with the number of sensors used, position on the body, and calibration. Our project is built in Unity and depends on SteamVR [11] and FinalIK [31], an inverse kinematics (IK) solver. A tethered connection to a PC drives the HTC Vive headset. SteamVR runs in the background to monitor and coordinate the positional data for all the Vive components: HMD, controllers, trackers, and base stations. We require two base stations for the exercises in this work, but we add a third to increase tracking precision. Scripting components of FinalIK link the joint positions of the player's avatar to their actual body positions, with 6 points of tracking: the HMD, the controllers, and trackers on the hips and feet.

To begin, a player must first put on the hardware using a minimum of four trackers: one on each foot, one above the knee of the rehabilitation leg, and one on the hip of the exercised leg. At the start, a player's avatar requires calibration to scale its size and orientation to match one's actual body. FinalIK facilitates this process: players stand in a "T" position with their arms outstretched to either side and squeeze the grip buttons to calibrate. The IK renders the avatar in a close approximation to the player's actual body, estimating a pose from the feasible positions of each segment of the avatar's virtual skeleton based on the current locations of tracking devices.

3.3 Training Environment

In our prototype, aesthetics are for practical utility rather than visual interest to train participants' attention solely on their exercise tasks. In our design, we center a sizeable virtual mirror upfront in the virtual training environment [15]. The mirror is a lens, providing users a framework for focusing on their movements. In the mirror, users study the control and movement of their virtual body, their reflection becoming the principal interaction dynamic of our prototype. To focus our study on participants' ability to control their avatar and complete the exercises, they are positioned directly in front of the virtual mirror within the scene. An exercise menu is to the left of the mirror, and on the right, there is an avatar instructor. The instructor avatar is the same model as the playable character but is rendered in a solid dark grey to stand out against the environment. Users embody the lighter translucent avatar, allowing them visibility through their virtual body to their environment.

The UI panel facilitates a players' selection of the four exercises included. Users select buttons by targeting them with a ray extending from the controller and depressing a trigger to open the selected exercise on the mirror. The UI panel of the mirror contains the name of the exercise selected and three values: Joint Angle, Number of Reps, Hold Time. Along the mirror's bottom edge are three other buttons: Start, Instruction, Stop. When selecting "Instruction," a recorded voice explains how to perform the exercise, while the instructor avatar animates an example performance on the right. When the player has understood the movements of the training, they select "Start" to begin the exercise and record their data. The "Joint Angle" fields populate with the angle calculations for their currently monitored exercise joint. As they start, counters for the "Number of Reps" and the "Hold Time" populate these associated fields in the UI. The typical hold time for an exercise is 5 seconds, and an audio cue is triggered when the hold time counter reaches the 5-second mark. After each repetition, the recorded voice counts the number of reps completed. When finished, the player selects the "Stop" button; the data collection ends, players then move on to the next exercise.

We relocate the instruction avatar and mirror above the player for prone exercises to render performances visible when lying down.

For these exercises, the animated instructor is at the top of the mirror. Each exercise follows the same format, playing audio and animations with each instruction. Users complete each training in sequence; the "Start" and "Stop" buttons begin and end a recording of the raw data from the tracked position of each Vive component.

3.4 Feedback and Data

We include two methods of data collection in this prototype: (1) raw data from the individual trackers recorded in JSON (JavaScript Object Notation) format, and (2) a complete recording of the player's avatar movements as an animation using the BVH file format [3]. We summarize exercise data in a scoreboard to conclude each session, compiling the quality and completeness of the entire session. For this summary, we calculate the total number of repetitions completed, the mean joint angle at extension, and the total time of held positions.

In the first method, we define each exercise by triangulating related tracker positions. For example, in the seated long arc quad exercise, we define the knee angle by creating vectors between two-tracker sets, hip-to-knee, and knee-to-foot, and calculate the angle between them. Within each exercise's natural range of motion, we define a neutral pose and an extended pose to create thresholds that trigger rep counting and hold times. Thresholds are relative to the goals and abilities of each patient and subject to change as their range of motion improves. The heel slide also monitors the knee angle in the other exercises, but from a prone rather than seated position. The straight leg raise works similarly but uses vectors from the head-to-hip and hip-to-foot to derive the angles of interest from the hip joint. Ankle pumps deviate from this format to calculate the changing distance of a single vector drawn from the foot to the knee. This method works best for exercises with significant changes in limb positions. Creating thresholds for the ankle pump exercise, which moves only the feet by pointing the toes downward and then pulling them back towards the ankles, is at the lower limit of the functionality of our current strategy.

In our second data collection method, we include a free asset package from the Unity Asset Store, *BVH Recorder* [8], to record the skeletal hierarchy of the avatar. Using the *BVH recorder* asset, derived from the Biovision Hierarchy for human motion capture file format, we record the player's exercise performance as an animation. We use two main components to our playable avatar. The first is the animation recorder component, and the second is an animation loader component with which an avatar can replay previously recorded movements. We use these functions to record animations of the demo exercises played on the instruction avatar. The BVH files are compatible with other motion analytics platforms and reviewable by a doctor or therapist.

4 USABILITY STUDY

We invited participants to engage with our prototype to examine system performance and design strategy in addition to a general sense of the feasibility of VR rehabilitation for lower limb exercises, which require participants to perform exercises in unusual positions for VR environments (e.g., laying down, sitting on a chair). Following a playtest of the project, participants responded to a survey and a semi-structured interview. We designed the study based on previous research into avatar embodiment [14, 33] because it is critically important to understand how users relate to their avatar in the virtual environment. Interviews of participants add nuance to the survey results.

4.1 Participants

We engaged six healthy volunteers under 30 (M = 22, SD = 3.32) to participate; one had previously received physical therapy for a broken knee. Genders included one female, three male, and two non-binary participants. All participants had previous experience with VR, while none had prior experience with full-body tracking or rehabilitation in VR.

4.2 Materials

Our survey uses a 7-point Likert scale ranging from "Strongly disagree" to "Strongly agree" scored from -3 to 3. We asked 24 questions about the experience focusing on the appearance and responsiveness of the avatar, the sense of ownership from control of the avatar, and enjoyment of the rehabilitation work in VR. Preceding the survey questions was the statement "During the experiment, there were moments in which…" followed by questions in the categories: body ownership, agency and motor control, tactile sensations, the location of the body, external appearance, illusion, and enjoyment. Our survey is modeled on the avatar embodiment questionnaire by Peck and Gonzalez-Franco [27], and includes additional questions following the body ownership scale by Roth et al. [33]. With the semi-structured interviews, we asked participants for feedback about the application, exercise training, and hardware. We combine the survey and interview to inform our design process and future work connecting the needs of users for ownership, agency and control, and enjoyment to the requirements of the rehabilitation protocol.

4.3 Procedure

Participants confirmed consent to volunteer and were given a brief introduction to the project and the purpose of our testing. We explained the avatar and the use of the trackers to connect their movement to the avatar. We provided explanations of data collection methods, requesting that participants follow instructions within the experience and complete the exercises as directed. They were introduced to the hardware, provided instructions for placing the trackers on their bodies, the use of the controllers, and adjustable headset features. We explained the calibration procedure and began the experience. Participants were guided through the calibration process and prompted to start the exercise training as needed. A team member ensured participants were safe and unobstructed by elements in the physical environment when moving from standing to seated and seated to laying down. Participants were allowed to explore and learn from the application at their own pace making selections from the task menu and following the instructions provided within the experience. When they finished all exercises, we encouraged participants to view the scoreboard summary before we ended the experience. Participants moved to a workstation to complete the survey and to a separate room for the interview.

4.4 Usability Study

We analyze survey results by grouping questions about body ownership, agency and control, and enjoyment together, calculating the mean for each participant. Using these values, we determine the mean for the group. Body ownership questions addressed the participants' sense that the virtual body belonged to them when seen either looking down at their avatar or in the virtual mirror. Participants 'somewhat agreed' with virtual body ownership questions (M = 1.14, SD = 0.82), and agreed more with measures for agency and motor control over the virtual body (M = 1.58, SD = 0.64). Participants found enjoyment in the experience of controlling the virtual body (M = 1.57, SD = 0.87) and reported an interest in using VR for rehabilitation in the future.

We queried participants regarding the visual and tactile continuity for sensations of tracker placement, asking if the trackers felt located on the body where they appeared on the avatar. To the statement: *"It seemed as if I felt the touch of the trackers in the locations where I saw them on the virtual body,"* all but one participant agreed. P2 "Somewhat disagreed" with this statement indicating the knee tracker deviated from this correlation.

The interviews echoed survey findings while highlighting limitations and opportunities for rehabilitation experiences in VR. In the interviews, participants expressed their enjoyment of the experience, with most finding it easy and fun to perform the exercises and control the virtual body. Participants could readily see the potential utility and benefits of the prototype for home-based rehabilitation: *"I think that is good if the data is collected and my physician will see the improvement or how I do the exercise; it would be a really good tool for rehabilitation"* (P1). Several participants brought up the idea that a doctor could review the data and animated recordings of exercise sessions asynchronously. One user suggested incorporating a doctor's presence simultaneously through a multiplayer mode where the doctor could virtually attend an exercise session in avatar form to give direct guidance. Interest in a therapist's oversight was among several signals emerging from the interviews pointing to the importance of trust. The consensus is that the application could 'definitely' benefit home-based rehabilitation and that *"this might be 20-30 years out"* (P3). The subtext of this projection connects ideas of value to an imagined flawless functionality and near ephemerality of hardware, where a tracker might be no more than a 'sticker' (P3).

Trust emerged as the dominant theme in participant feedback, and trust in human-computer interaction (HCI), as in real life, is hard to win and easy to lose [52]. Our users expressed a hesitancy to fully embrace VR for rehabilitation citing concerns for the accuracy of current hardware and observing that even greater accuracy and more sensitivity to the subtleties of the exercises would be necessary for a genuinely robust VR rehabilitation experience. Despite their concerns and our prototype's current limitations, our participants enjoyed the experience while successfully and independently completing the exercise protocol.

Throughout their feedback, participants reiterated the importance of straightforward, easy-to-follow directions. They noted the advantages of VR to deliver experiences that support both the physical and mental aspects of rehabilitation work, citing accessibility and accurate guidance as primary factors. Controlling the avatar with one's movements and watching the effects in the virtual mirror is the fundamental interaction of the experience; it is ordinary and expected in reality but magical and engaging in VR. Assistive functions, such as counting reps and hold times for each exercise, were noted to reduce the workload and related anxiety during task performance. Our users were satisfied by the generic and straightforward humanoid avatars but recommended creating additional animations to detail the body areas involved in each exercise. They also suggested using a natural human voice rather than the digital one for audio instruction and creating an environment with more emotional interest. The paired-down environment was an attribute in comments about clarity of purpose within the virtual space, but its austerity did not appeal.

5 DISCUSSION AND CONCLUSION

Motion capture and real-time data analysis are viable and valuable ways of delivering VR rehabilitation. We find that IMU sensors perform well when monitoring gross motor movements, and the raw data is precise. However, in designing thresholds for real-time feedback to support training bodies of varied size and ability, our ability to utilize IMU data precision fully is constrained by the need to accommodate wider variance. Adjusting for variabilities within and between users could be refined by leveraging work in Artificial Intelligence (AI) and Machine Learning (ML) to personalize exercise guidance and modify protocols to match patients' changing needs and abilities. Continued development of our prototype can also incorporate educational design strategies for goal-oriented motor skills development, which classified motor skills by (1) the precision of the movement, (2) the beginning and endpoints of the movement, and (3) the stability of the environment within which the movements are performed [24, 34]. In addition, we find applications of this kind can benefit from employing a multimodal sensor strategy to monitor both isometric and isotonic exercises. By integrating other sensor modalities such as electromyography (EMG) [18], or electrical impedance tomography (EIT) [54] with IMU sensors, we can gain insight into the specific muscles used and the intensities of their engagement.

The currently available hardware and software used in our prototyping are not ideally suited to our application, but their shortcomings better illuminate our needs. We rule out optical and depth-sensing solutions for motion capture because errors from occlusion are untenable for our design. However, while cameraless, the Vive system still depends on base stations operating from the outside-in to track a patient's movements. Because of this, occlusion can still occur, and tracking can be lost. While tracking glitches are usually minor, their distortions can be extreme for rendering the avatar. Whether comical or disturbing, distortions of the virtual body from tracking errors do not go unnoticed by users and can radically disrupt the user's sense of presence in VR [38]. Often cited in work of this kind, presence is key to effective engagement in immersive learning environments [1]. Despite the shortcomings of available low-cost hardware, we believe solutions to the current weaknesses are feasible, and our design strategy is extensible for supporting lower body rehabilitation in VR.

We find that the viability of rehabilitation experiences in VR depends not only on the quality and accuracy of hardware and software but also on users' receptivity to engaging with these technologies for this purpose. Our results suggest that real-time feedback generated from detailed monitoring of exercises in VR can be exciting and enjoyable to users, even in the simple form of our prototype. Participant interviews reveal a natural curiosity for engaging our prototype; however, creating a more conducive environment and designing interactive experiences around the rehabilitation work will be necessary to sustain interest over time. To continue this work, we look to game design for the interaction strategies that can maintain long-term engagement and motivate patients to be consistent in their daily rehabilitation practice [2, 20, 23]. We have learned from our participants the importance of designing for trust and the necessity of maintaining a user's confidence in the system. Our participants value accurate reflections of their actual movements in the virtual mirror but are unconcerned about realistic depictions of their actual bodies. Reflecting on these observations, we see that the foundation of VR rehabilitation is not in the details of the environment or design but in the system's ability to understand a patient's effort accurately and communicate this understanding appropriately.

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