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Virtual Reality-Powered Wrist Therapy: Developing a Therapist-Driven Exit-the-Room Serious Game with Hand Gesture Interactions

René Baranyi [1,*], Christoph Hirber [1], Lukas Roehrling [1], Christoph Aigner [1], Dominik Hoelbling [2], Werner Hoerner [3] and Thomas Grechenig [1]

1 Research Group for Industrial Software (INSO), TU Wien, 1040 Vienna, Austria; christoph.hirber@tuwien.ac.at (C.H.); lukas.roehrling@tuwien.ac.at (L.R.); christoph.aigner@inso.tuwien.ac.at (C.A.)
2 Research Industrial Systems Engineering (RISE), Concorde Business Park F, 2320 Schwechat, Austria
3 Human & Digital, Vienna, Argentinierstrasse 21, 1040 Vienna, Austria; werner.hoerner@humanomed.at
* Correspondence: rene.baranyi@inso.tuwien.ac.at

Abstract: Wrist injuries, driven by factors such as an aging population and the popularity of high-impact sports, have become increasingly prevalent. In response, this study focuses on developing a serious game for wrist injury rehabilitation within a virtual environment, aiming to enhance motivation and therapeutic adherence while highlighting the potential of virtual rehabilitation. Extensive literature research and the involvement of five experts during the game's design led to the creation of "WristBreakout", which successfully integrated 13 out of 15 recommended movements into gameplay. In addition, the technical feasibility of the VR headset "MetaQuest" within the domain of wrist rehabilitation was shown. A preliminary evaluation with six healthy participants showed positive results in terms of usability and acceptance (SUS average was 69; UES categories were between 3.97 and 4.77). This work contributes to the broader context of serious games and virtual reality (VR) applications in healthcare, exemplifying how technology can positively impact the rehabilitation experience.

Keywords: serious games; prevention; rehabilitation; wrist; VR

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Citation: Baranyi, R.; Hirber, C.; Roehrling, L.; Aigner, C.; Hoelbling, D.; Hoerner, W.; Grechenig, T. Virtual Reality-Powered Wrist Therapy: Developing a Therapist-Driven Exit-the-Room Serious Game with Hand Gesture Interactions. *Appl. Sci.* **2024**, *14*, 4780. https://doi.org/10.3390/app14114780

Academic Editors: Redha Taiar, Roxana Miclaus and Elena Amaricai

Received: 15 April 2024
Revised: 8 May 2024
Accepted: 22 May 2024
Published: 31 May 2024

1. Introduction

A study by Christopher Stephen Crowe et al. in 2019 [1] compared the incidence of hand and wrist injuries in 2017 with data from 1990, revealing a global trend of decreasing injury rates. However, regions with a low socio-demographic index exhibit a contrasting trend. While Central Europe reports an incidence of 7.6 per 100,000 inhabitants, in South Asia, this figure stands at 25.9 per 100,000 inhabitants. In 2019, the most frequent anatomical sites for prevalent fractures included the patella, tibia or fibula, and ankle, followed by fractures in the femur (excluding the femoral neck) and the hand, wrist, or other distal hand parts, as reported by Wu and colleagues [2]. In Austria, for instance, around 366,000 individuals experienced bone fractures in that same year, with approximately 10% of these fractures occurring in the wrist region, according to the Global Burden of Disease Collaborative Network [3]. Many sports that have gained popularity in recent years, such as mountain biking and various contact sports, pose a substantial risk of causing lasting wrist injuries during falls [4]. Suffering from various wrist injuries often compels patients to temporarily set aside their daily hand-related tasks. According to statistics from the European Injury Database (IDB) and research conducted by Oberfeld et al. [5], the European Union alone witnessed approximately 8.8 million such cases in the years 2006–2007, constituting around 21% of all recorded injuries. Given the vital role of the wrist in everyday life and the substantial strain it endures, injuries and strain-related issues in this area present an omnipresent and serious concern. Consequently, the prompt and precise identification of wrist injuries is crucial. Prolonged pain and limitations can significantly impede the quality of life and the use of hands in daily life and professional endeavors for those affected [6].

Wrist injuries, owing to their complexity and constant use, can lead to trauma if not properly rested, often necessitating surgical intervention. Subsequently, rehabilitation becomes crucial [7]. Rehabilitation primarily centers around mitigating the impact of a medical condition on an individual's daily life, improving their capabilities, and reducing the extent of impairment [8]. Traditionally, functional rehabilitation encompasses therapy counseling and participation in physical exercises or tasks, either under professional supervision or carried out independently [9]. Rehabilitation exercises, when required, often become monotonous, and the motivation and resilience of individuals tend to wane over time. Nevertheless, this challenge can be effectively tackled through the integration of serious games [10]. Patients' post-treatment or rehabilitation processes vary depending on the chosen treatment approach [11].

Serious games extend beyond simple entertainment, integrating interactive mechanics typical of video games to provide additional benefits to users [12]. Meijer et al. [13] conducted research on how serious games and wearable technology impact the rehabilitation of individuals with bone and soft tissue injuries. Their study involved an analysis of 12 relevant studies, revealing promising outcomes, particularly regarding therapy adherence. A study utilizing a wooden hand attached to an industrial robotic arm together with a Leap Motion Controller (LMC) has shown that such a setting is a viable and cost-effective solution for wrist rehabilitation [14]. Herne et al. researched the effects of a virtual reality-based serious game aimed at upper-limb rehabilitation after a stroke. Their results showed that the game increased enjoyment and motivation for patients, encouraging them to participate in therapeutic exercises for rehabilitation [15].

Serious games have a wide and varied range of applications across multiple fields, including training and simulation, education, enhancing human performance, strategic communication, and healthcare [16]. A meta-analysis [17] highlighted and determined that the use of serious games and virtual reality can motivate patients to engage with their therapeutic needs, improve physical fitness, and reduce disease symptoms. Within the domain of serious games for health, various areas are covered, including their application in knee rehabilitation using smartphones, as shown in [18], or their use in stroke recovery as part of the rehabilitation process with the additional utilization of smartphone sensors, as demonstrated in [19]. Serious games are also employed in addressing cerebral dysfunction, as discussed in [20], cognitive impairments [21], and supporting nutritional education [22]. There are also multiple approaches to implementing serious games for enhancing sports activities [23,24].

The Leap Motion Controller [25] is already being widely used for hand rehabilitation, with its optical hand-tracking module being utilized for capturing precise hand and finger movements [26]. Studies have shown its effectiveness in upper extremity mobility improvement through video game-based therapy, particularly in stroke rehabilitation [27]. Its relevance continues, with research demonstrating its impact on pinch grip in stroke patients [28] and its utility in other areas like Parkinson's disease. The LMC also has proven to be a valuable virtual reality tool for enhancing hand gestures and motor movement, with high feasibility, attendance, and satisfaction in chronic stroke patient rehabilitation [29].

Another solution by Correa et al. [30] uses the Gear VR headset in combination with an LMC. The goal of their game is to pick up and drop fruits into a basket using grasp movements. It was evaluated with cerebral palsy patients, who showed good acceptance of the system.

Additionally, it is recognized as a cost-effective option for wrist rehabilitation, capable of accurately recognizing various gestures in post-stroke patients and improving upper-limb functionality [14,31,32].

Therefore, this paper discusses the use of a serious game to support rehabilitation in the context of hand/wrist rehabilitation. The proposed solution uses a MetaQuest head-mounted display (HMD) and integrated cameras to capture hand and wrist movements.

The subsequent sections are structured as follows. Section 2 describes the materials and methods utilized to obtain the results outlined in Section 3, together with a discussion in Section 4. Afterward, an outlook is provided in Section 5.

1.1. Related Works

As part of a review publication by Sheng et al. [33], different serious gaming solutions for stroke rehabilitation were identified, but the study does not mention any specific MetaQuest VR solution.

Gonçalves et al. designed a serious game for the rehabilitation of upper-limb function, integrating the Leap Motion controller (LMC). The primary goal of this game is to infuse the rehabilitation process with enjoyment and motivation. Within this virtual kitchen scenario, players are tasked with creating a cake, engaging in six distinct activities targeting various upper-limb functions: reaching, grasping and releasing, moving, pouring, and circular displacement. This innovative solution is aptly named “You Can Cook Again” [34].

Khademi et al. customized the popular game “Fruit Ninja”, employing the LMC as a hands-free input device. This adaptation was chosen to inject an element of enjoyment and suitability into rehabilitation exercises, given the game’s demand for purposeful hand movements. With the hand-tracking data provided by the controller, individuals recovering from strokes can effectively train their finger mobility. In the original game, players slice through fruits displayed on the screen using click-and-drag actions (in the desktop version) or touch-and-drag actions (in the mobile version) [35].

The authors of [36] introduced an innovative serious game for wrist and hand rehabilitation to address stroke-associated exercises. It combines cognitive and physical therapy using the LMC and a desktop or laptop computer. The game’s development follows a three-phase user-centered design approach, with input from therapists. It offers various levels, each requiring specific hand and wrist movements that are used to control the avatar in a jump-and-run game, enhancing cognitive training. Overall, 44 requirements were identified, showing the solution’s potential for effective rehabilitation and as a foundation for future serious game development in this field.

To aid in wrist rehabilitation, a combination of smartphone technology and a serious game was introduced in the study by Baranyi et al. [37]. The game, known as “Wristdroid”, offers various exercise levels monitored through a smartphone held in the user’s hand.

Similarly, an alternative solution known as "DroidGlove" was developed [38]. This mobile application is designed for wrist rehabilitation and allows medical professionals or therapists to record sequences of movements or exercises, which patients can access through their mobile devices.

The solution by Shen et al. [39] supports hand rehabilitation with an AR application. In this setup, specially developed digital data gloves are utilized to monitor the hand movements of patients and gather their data. Augmented reality technology is employed to create a highly adjustable environment, offering tasks with varying degrees of difficulty for patients to engage in rehabilitation exercises.

The study detailed in [40] introduced a VR system for upper-limb rehabilitation. This immersive system utilizes hand gestures captured with the LMC when interacting with virtual objects and is capable of emitting odors upon achieving set goals. This is achieved through the Multi-Fragrance Olfactory Display (MFOD) device developed by the authors. A VR walking game was created for stroke recovery patients by So et al. [41]. It was assessed by twenty professionals, including physiotherapists, occupational therapists, and prosthetic-orthotic therapists, through surveys and interviews. Eighty percent of these therapists concurred that this VR game could enhance their ability to treat more post-stroke patients. The initial version featured a head-mounted display (HMD) for the VR experience. Further evaluations confirmed the potential advantages of VR games in the clinical treatment of stroke recovery patients. The paper by Batista et al. [42] outlined the creation of a serious game designed to assist in rehabilitating patients with hand motor issues. The game uses an electromyography device for gesture recognition, enhanced by a newly developed system supporting hand and wrist rehabilitation exercises.

In the paper by Corona et al. [43], an integrated framework was developed for wrist rehabilitation in Juvenile Idiopathic Arthritis (JIA) patients. It includes four video games, controlled with gestures captured by the LMC, and modules that allow therapists to customize exercises, record patient actions, and analyze sessions.

Farahanipad et al. [44] focused on creating “HandReha”, an innovative game-based system for wrist rehabilitation. It utilizes a web camera to automatically recognize pre-set hand gestures, enabling users to control an avatar in a three-dimensional maze-run game.

1.2. Novelty of the Solution

The solution described here offers novel approaches for the development of a serious game that supports hand rehabilitation exercises utilizing a MetaQuest VR headset [45]. The proposed solution offers a new game type (escape room setting) not yet used within a rehabilitation setting, which also includes concurrent gameplay without considering different levels or mini-games. Our solution can, therefore, be extended horizontally (new riddles and interaction within the current rooms) or vertically (new rooms or places). Different movements are included in this setting compared to other solutions where specific movements are tied to a mini-game or level. In addition, many previous solutions also lack definitions/descriptions of requirements or movements and their projections within a serious game. Our solution offers an overview of these exercises and their alignment with specific in-game interactions. In addition, using a “MetaQuest” VR headset with built-in sensors is also new. It demonstrates the technical feasibility of using such a hand and wrist rehabilitation solution. Other projects use sensors like the LMC, built-in smartphone sensors, or even proprietary self-built hardware. Additionally, current solutions often focus on a specific disease or pathology and do not explicitly address hand or wrist rehabilitation in general. Thus, the research presented here should be viewed as a potential foundation for creating a serious game focused on hand and wrist rehabilitation. This leads to the research question: Can a serious game developed using a “MetaQuest” headset (or any VR serious game) fulfill the requirements specified by therapists? Table 1 summarizes the solutions in the related works and also highlights the differences between these solutions and the serious game presented here.

Table 1. Comparison and overview of state-of-the-art solutions, including the work presented here.

Author	Reference	Sensor	Focus on	Game Type	Req. Defined Explicitly	VR	Gaming Context
Gonçalves et al.	[34]	LMC	Upper-limb rehabilitation	Cooking	No	No	Game/Room
Khademi et al.	[35]	LMC	Stroke rehabilitation	Fruit Ninja	No	No	Level-Based
Baranyi et al.	[36]	LMC	Stroke rehabilitation	Jump and Run	Yes	No	Level-Based
Baranyi et al.	[37]	Smartphone	Wrist rehabilitation	Various	Yes	No	Mini-Games
Deponti et al.	[38]	Smartphone	Wrist rehabilitation	N/A	No	No	N/A
Shen et al.	[39]	Data Glove	Hand rehabilitation	N/A	N/A	No	N/A
Covarrubias et al.	[40]	OR, LMC, Own device	Upper-limb rehabilitation	N/A	No	Yes	N/A
So et al.	[41]	Mark1	Stroke walking	Walking	No	Yes	Levels
Batista et al.	[42]	Myo	Hand and wrist rehabilitation	Various	No	No	Mini-Games
Corona et al.	[43]	LMC	JIA Wrist	Various	Partly	No	Mini-Games
Farahanipad et al.	[44]	Webcam	Wrist rehabilitation	Maze runner	No	No	Levels
Correa et al.	[30]	Gear VR	Cerebral Palsy	Catching Fruits	No	Yes	Mini-Game
Baranyi et al.	This publication	MetaQuest	Hand and wrist rehabilitation	Exit the Room	Yes	Yes	Game

2. Materials and Methods

The methodology contained various steps, including requirements engineering, which was based on qualitative and quantitative aspects and an iterative prototyping process. The entire process utilized a user-centered design (UCD) approach [46], with therapists involved in the development. The therapists were questioned based on their expertise and availability. Formulating the sampling was found to be crucial [47]; therefore, the sampling was defined to match the following constraints: expertise with hand rehabilitation, experience in the field, no age restrictions, and availability. A few therapists were approached via e-mail based on internet research. In addition, another therapist known to one of the research team members was also included and helped find other possible participants (see Table 2 for an overview of the final participating therapists). The authors assume that there was no bias associated with acquiring the exercises and requirements for this serious game. An interview guideline was defined, and all therapists were interviewed, gathering feedback on possible requirements, information about wrist injuries, associated exercises, the overall process, and serious gaming/VR aspects (such as their experience).

Table 2. Overview of all participants in the different phases.

ID	Age	Gender	Type	Working Years	VR Experience
P01	55	M	Physiotherapist	33	N
P02	37	F	Physiotherapist	15	N
P03	38	F	Occupational therapist	9	N
P04	26	F	Occupational therapist	3.5	N
P05	60	F	Occupational therapist	36	Y
P06	42	M	Evaluation Testuser	N/A	Y
P07	30	M	Evaluation Testuser	N/A	Y
P08	38	M	Evaluation Testuser	N/A	N
P09	33	M	Evaluation Testuser	N/A	N
P10	20	F	Evaluation Testuser	N/A	N
P11	31	M	Evaluation Testuser	N/A	Y

After defining the initial requirements and corresponding movement patterns used within current rehabilitation exercises, the game idea was developed. The outcome was a VR game utilizing the “MetaQuest 2” VR headset. This device was chosen because of its availability and because one of the authors had already used it in another context. After defining the game narrative and prerequisites, the movement patterns were mapped into in-game movements. Since not all identified patterns could be transferred, the focus was on the remaining ones. Subsequently, the prototype was developed.

The overall setup included the “MetaQuest” head-mounted display (HMD) for the patients to wear. The game was tested on the “MetaQuest 2” and “MetaQuest 3” devices, which showed an equal gaming experience. The controllers are unnecessary because the game is controlled by hand movements (captured by the included cameras of the “MetaQuest” headset). By moving one or both hands, the avatar within the game is controlled, and interactions within the environment are performed. The movements used were defined by the necessary exercises identified by the therapists. The game was developed using the Unity game engine [48]. Within a game menu (by making a peace gesture), different settings can be accessed. The game can be saved, the tutorial can be conducted again, some background information can be retrieved, and more additional information about playtime can be displayed. Different exercises (movements) are currently included and mapped to individual actions within the game (see Figure 1 for an overview of the setup and architectural components).

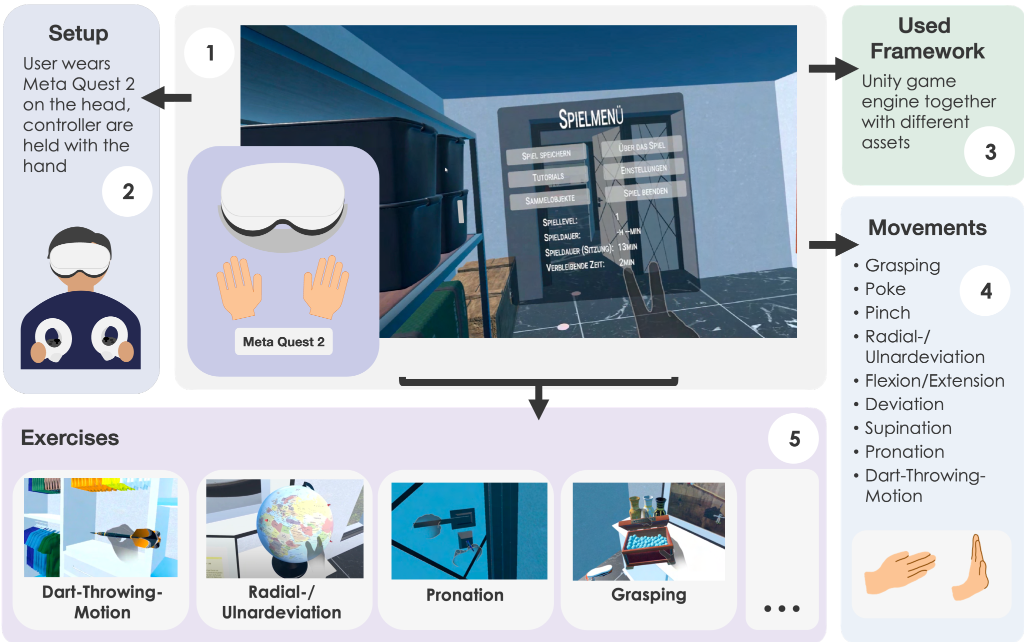

Figure 1. Overall technical setup and architecture, including the main menu and examples of integrated movements.

Succeeding the development phase, a short evaluation with a playtest was conducted to gain preliminary insights into design and usability aspects. Students and university members were recruited (utilizing a convenience sample) to participate. They had the opportunity to play the game and give feedback through two questionnaires immediately after a play session. In addition, they were asked if they encountered any problems. Participants were individually invited to the researcher's lab for the play session and an introduction to the research (the purpose of the research, its background, and a basic introduction to VR). Participants were then given a "MetaQuest 3" headset and a consent form, which needed to be signed to proceed further. Then, they put on the headset where the serious game had already been launched and was in the starting state, showing the menu. Then, users were asked to complete the initial tutorial in the game. After they finished this tutorial, the game itself started, and the participants were required to play the game for 15 min. Participants also could return to the tutorial if they needed additional information, but none of the participants did this. The authors only assisted if participants requested help. After the play sessions, a short interview was conducted (targeting major problems), and two questionnaires were given out. For this evaluation, two established questionnaires were chosen—the short form of the "User Engagement Scale" (UES) and the "System Usability Scale" (SUS). With the SUS, it has been shown that the first 4–5 participants are likely to identify about 80% of the problems, with additional subjects increasingly less likely to uncover new issues, especially since severe problems tend to be detected early on by the initial users [49]. The UES was initially developed containing 40 questions by O'Brien and Toms [50] to measure engagement within a serious game and was later reduced to 12 basic questions [51] (which were used within this research). Their scale dimensions include "Focus of Attention" (FA), "Perceived Usability" (PU), "Aesthetic Appeal" (AE), and "Value of Rewards" (RW). The SUS mainly targets user experience and usability [52].

3. Results

The sections below present the results obtained using the previously described methodology. Overall, a serious game was developed and controlled through various movements detected by the cameras in the "MetaQuest" VR headset.

3.1. Requirements

Throughout the different phases of the research, different requirements were identified based on the therapists' feedback. Table 3 provides an overview of the proposed requirements. These requirements were partially included within the overall concept, design, and prototypical implementation of the serious game.

One important aspect is the possibility of reviewing the performance/movements of the patients. This might be conducted differently, e.g., through streaming (R01). The game should be easy to use and understand for patients (R02) and deliver clear and precise instructions on how the movements should be performed and how the exercises should be conducted (R03). In addition, the achieved goals should be displayed for motivational purposes, e.g., a successful combination of items (R04). Since different patients require individual difficulty settings (e.g., at the beginning of rehabilitation or the end), this should also be incorporated (R05). Therefore, general game settings should also be adaptable to individual needs (R06). The overall game and its underlying mechanics should also serve as motivation for patients and not demotivate users, e.g., when they are not yet able to do something (R07). The exercises that need to be performed while playing the game should be performed correctly (R08)—badly or incorrectly performed movements may have a negative impact on the healing process. Patients suffer different and individual pain types while performing movements. This must also be incorporated within the game, i.e., a patient should only perform movements when not experiencing severe pain (R09). One problem that might arise while performing exercises is hand swelling, which should result in stopping the exercises (R10). The game should be stoppable at any point if complications arise, e.g., the patient is not feeling well (R11). The exercises should also include the upper extremities' distal and proximal movements (back and forth to the body center) (R12). Patients should also provide information about their well-being or pain during playing, e.g., to adapt or check exercises (R13). Overall, the game sessions should be limited to 15 min each—too much exercise is counterproductive (R14). Exercises involving symmetrical or coordinated movements should be included, specifically to stimulate or engage neurons (R15).

Besides these identified requirements, the goals of this solution were also formalized by therapists as follows: (A) Work reintegration and everyday coping. (B) Swelling and pain reduction. (C) The range of motion after successful therapy should be equivalent in a side-by-side comparison. (D) It should be usable for patients with complex regional pain syndrome (CRPS).

Table 3. Identified requirements gathered from the therapists and their inclusion within the prototype (Y = included, N = not included, P = partially included).

ID	Description	In Prototype
R01	Review possible (via streaming) for therapist	Y
R02	Game should be easy to use and easy to understand	P
R03	Good and clear/precise instructions should be given	P
R04	Achieved goals should be displayed	P
R05	Difficulty should be adaptable to user needs	N
R06	Game setting itself should be adaptable	N
R07	Game and mechanics need to be motivating for the patients	Y
R08	Exercises should be performed correctly	Y
R09	Pain thresholds of patients should be considered	P
R10	Control of hand swelling must be incorporated	N
R11	Game should be able to be stopped in case of complications	Y
R12	Involvement of the upper extremities from distal to proximal	Y
R13	Patient survey on well-being and extent of pain during exercises	N
R14	Game sessions should not be longer than 15 min	Y
R15	Symmetric movements for neurons	P

3.2. Movements

Different movement patterns used in rehabilitation exercises were identified through expert interviews. These patterns were transferred into in-game movements, which are conducted throughout the VR escape game. One identified movement was opening bottles, which was transferred into the game as the rotation of a safe combination (M1). Making a fist was another movement transferred into the game as a grasping gesture (M2). The radial/ulnar deviation was adapted by spinning a globe or using the teleportation function to move from one place to another (M3). Flexion/extension was included as swiping pills within the game (M4). The dart-throwing gesture, found to be very important, was integrated by throwing objects, e.g., throwing an object at a glass (M5). The exercises of opening and closing a zipper were included through the possibility of rotating a faucet (M6). The exercise of flipping through the newspaper was included via the positioning of pins (M7). Pouring from a container was included through emptying boxes (M8). Lifting objects were also included in the grasping gesture (M9). Playing the piano was included as a normal exercise, which involved the same in-game movements and tapping a touchpad on a laptop (M10). A cutting/hacking motion was included through opening/closing doors (M11). A praying exercise was included with the same gesture to activate the pause function (M12). A stirring gesture was included to turn around a crank (M15). While the aforementioned gestures could be included, some others could not. Supporting gestures like sliding a door could not be included (M13). The circular movement was also not possible to include (M14) (see Table 4 for an overview of identified exercises and their mapping to in-game movements).

Table 4. Important identified movements and their integration within the game.

ID	Exercise	In-Game Movements
M01	Opening bottles	Rotating a safe lock
M02	Making a fist	Grasping objects
M03	Radial/Ulnar deviation	Spinning a globe, teleporting
M04	Flexion/Extension	Swiping away pills
M05	Dart-throwing movement (DTM)	Throwing objects
M06	Opening/closing zip fasteners	Rotating a faucet
M07	Flipping through newspapers	Positioning pins
M08	Pouring from a container	Emptying boxes
M09	Lifting objects	Grasping objects
M10	Playing the piano	Playing piano, tapping a touchpad
M11	Cutting motion/Hacking motion	Opening doors
M12	Peace gesture	Pausing the game/Menu
M13	Supporting movement (e.g., sliding a door)	Not included
M14	Circular movement of the hand	Not included
M15	Stirring	Turn a crank

3.3. Prototype

For the serious game presented here, different exercises were identified, selected, and integrated into a game using the hand-tracking sensors of the "MetaQuest" VR headset. At the beginning of the game, the players find themselves in an environment designed to familiarize themselves with the interaction possibilities offered by the serious game. This environment serves not only as a tutorial but also as the starting point for the game itself. It comprises six scenes dedicated to instructing the player on various interaction techniques. These scenes encompass learning to use gestures, manipulating and interacting with objects, and understanding movements within the virtual house. The journey commences in the entrance area, marked by floor indicators that serve as teleportation points and key locations in the game. To complete the prototype, two puzzles must be solved: playing a four-note sequence on a piano and using a four-digit code to open the safe, with the latter marking the finalization of the game. An open-ended design was incorporated to provide room for expansion, allowing for the potential integration of additional levels, thus diversifying the therapy sessions. Figure 2 gives an overview of the included rooms and their corresponding objects. As an example, various boxes are scattered throughout different rooms within the game, all of which need to be opened. Some of these boxes contain clues or keys that are essential for progressing further in the game. This element also adds a layer of exploration and discovery to enhance the gameplay experience.

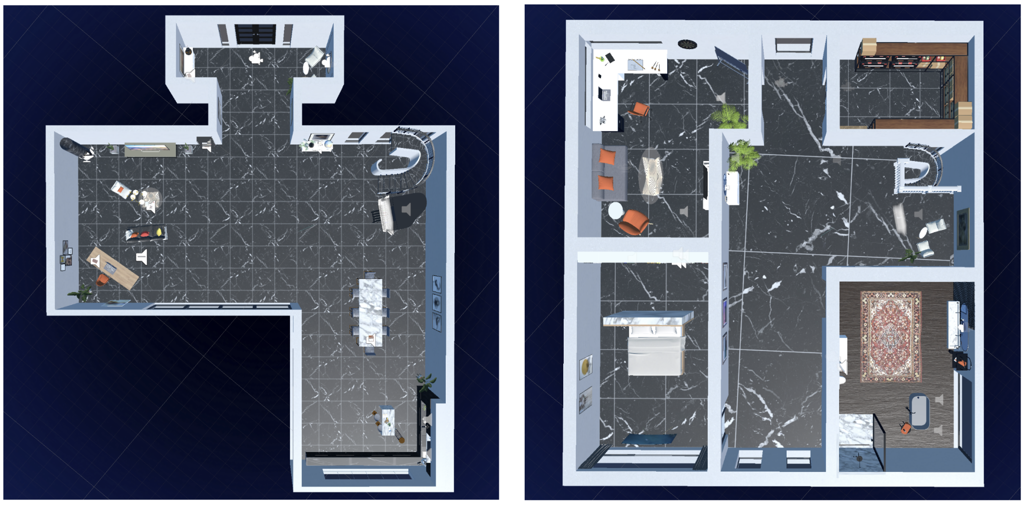

Figure 2. Game setting and room overview as a top-down view; each picture represents one floor where users can interact with the environment and switch between using the included stairs.

3.4. Evaluation

To obtain initial feedback from users, two questionnaires were handed out after short individual playtesting sessions with all participants.

In the context of the SUS evaluation, there was a wide range of perceptions. The SUS scores ranged from 50 to 85 (see Table 5), with an average of 69, which is considered satisfactory but not good or excellent. The UES delivered preliminary results with averages ranging from 3.97 to 4.77 across all dimensions (See Table 6). The average of the Focus Attention (FA) dimension was 4.15, indicating good attention focus on the application during its use. The average of the Perceived Usability (PU) dimension was 3.97, which was the lowest value among all UES areas. This score is considered satisfactory but indicates some shortcomings in usability, which aligns with the SUS results. The average of the Aesthetic Appeal (AE) domain was 4.1, indicating good aesthetic appeal and that users found the design pleasant and engaging. The average of the Reward Worthiness (RW) dimension was 4.77, the highest average value among all dimensions, indicating that users considered the information or rewards provided to be worthwhile.

These results were also supported by feedback from the participating users. One major aspect mentioned by all participants was the difficulty of moving/teleporting with the given gesture. Although this was part of the tutorial, there were still a lot of problems while using it in the game. Another aspect that was mentioned was the possibility of losing objects while moving around. When this happened, it was difficult to retrieve or find them if unnoticed (e.g., while teleporting and holding an object in the other hand). Another problematic aspect mentioned was the lack of clear information (i.e., goals) or support to solve riddles. Additionally, the lack of ability to interact with everything was also mentioned as unclear (e.g., not all drawers and chests can be opened).

Table 5. Individual SUS results, including overall scores and their interpretation.

Part.	SUS	Interpretation
P06	50	Poor
P07	67.5	Ok
P08	70	Ok
P09	65	Ok
P10	77.5	Good
P11	85	Excellent
Average	69	Ok

Table 6. Individual UES results, including their averages (FA = Focus Attention; PU = Perceived Usability; AE = Aesthetic Appeal; RW = Reward Worthiness).

Part.	FA	PU	AE	RW	Average
P06	4.6	4.3	5	5	4.73
P07	3	4.3	3.6	4.3	3.80
P08	4	3.3	4	5	4.08
P09	3.3	5	3	4.3	3.90
P10	5	4.6	5	5	4.90
P11	5	2.3	4	5	4.08
Average	4.15	3.97	4.1	4.77	

4. Discussion

This paper presents a novel approach to improve the physical therapy process by developing a serious game specifically designed for wrist rehabilitation. Utilizing the "MetaQuest" VR headset, the developed game integrates a variety of identified movement patterns that mirror those used in traditional physical therapy settings. The research included a thorough review of existing serious games aimed at wrist rehabilitation and involved close collaboration with both physical and occupational therapists throughout the different phases. The resulting prototype, developed within the Unity development platform, features an escape-the-room-style game that employs specific movements detected by the "MetaQuest" headset's advanced hand-tracking sensors. Technically, our results confirm that the standard "MetaQuest" (2 and 3) headset and its integrated sensors can effectively control serious games tailored for wrist and hand rehabilitation, offering a functional and engaging therapeutic tool.

The game's design incorporates the engaging concept of an escape room combined with a compelling narrative to capture the interest of patients across different age groups, encouraging consistent participation in prescribed exercises at home or together with a therapist. This motivation is crucial for the effectiveness of home-based therapy. The project leveraged insights from a collaboration with five expert therapists and an extensive review of the literature on wrist injury rehabilitation, as well as six participants within an evaluation, enriching the game's content with effective therapeutic exercises. This collaboration allowed us to include a variety of precise movements, such as the complex dart-throwing motion, which enhances the game's therapeutic value and had not been adequately addressed in previous serious games.

Moreover, the use of "MetaQuest" as the chosen platform enables patients to engage in therapeutic activities virtually anywhere, providing flexibility and convenience without the need for additional hardware. This adaptability makes it an excellent option for patients who may find frequent visits to therapy centers challenging. The game's development also included a detailed survey of professional therapists, whose insights were invaluable in integrating clinically relevant exercises into the game. This comprehensive approach ensures that the game not only engages patients but also effectively meets therapeutic needs, potentially transforming how wrist rehabilitation is conducted. Additionally, the versatility and portability of the "MetaQuest" system allow for a broad implementation of this therapy modality, further extending its reach and impact in the field of rehabilitation.

4.1. Key Findings

This paper presents a solution for supporting hand rehabilitation therapy by creating a serious game within a VR environment that is controlled by the "MetaQuest" VR headset, which contains and includes diverse movement patterns. The commercial off-the-shelf sensor used was robust enough to collect rehabilitation movements, which were discussed with involved therapists. To create a serious game within such a VR setting, different requirements, as well as important current exercises and movements, were identified with the help of participating therapists. Based on these findings, interactions and in-game movements were identified and integrated. The dart-throwing movement (an important gesture in hand rehabilitation) was also included within the game setting. The analysis of the exercises found that not all required wrist movements could be incorporated into the game due to technical limitations. For instance, support movements could not be simulated in virtual reality due to the lack of physical resistance. Additionally, circular wrist movements had to be excluded. The idea to lift and rotate liquids or other objects in a container was not feasible due to Unity's limitations in handling fast-rotating objects within a specified container. Testing revealed that rotating elements in the container could be too intense, potentially causing liquids to spill through the container walls, which would significantly reduce the game's realism and overall quality. An additional movement of opening and closing buttons could also not be used within the VR setting (capturing of fingers is not sufficiently accurate). Overall it was shown that the "MetaQuest" VR headset and gameplay within a VR setting can be used effectively.

4.2. Limitations

Although the proposed solution seems promising, further research is needed to address the identified limitations. The requirements and gathered feedback are considered independent of the sample. However, it should be mentioned that one limitation is the sample selection, which is considered a convenience sample and is not representative in terms of gender or age. Also, the quantity of the sample size itself (specifically for UES) is a limitation, which should be addressed in future work by including more participants in playtesting sessions. A major advantage of including therapists in the requirement analysis is their increased knowledge about the problem space and their expertise in finding solutions for incorporating exercises into a serious game. However, the therapists were not included in the usability evaluation, which can also be seen as a limitation. The usability evaluation could also benefit from a more diverse sample of participants and an extensive evaluation period to gain more insights into the VR game and its usage. In addition, the demographics and the recruitment of only healthy participants are also limitations in terms of the presented results. This currently restricts the ability to answer to what extent the rehabilitation of wrist injuries is supported through the usage of this VR serious game. To answer this, a clinical trial or intervention study is necessary. A subsequent study should also include therapists to improve the overall quality and results. In conclusion, the results seem promising and show great potential in using a serious game with the MetaQuest sensor, but further research is necessary to address the mentioned limitations. Overall, this publication should be seen as a good starting point for further advancements and additional research in VR utilizing "MetaQuest" to support the wrist and hand.

5. Outlook

The prototype presented in this work represents an initial step toward wrist rehabilitation in virtual reality therapy. However, the scope is limited, and personalization for individual patients is restricted. To enhance the practical utility of the serious game, it would be advisable to incorporate patient-specific therapy data and adjust the prescribed exercises accordingly (e.g., use or remove specific movements). Furthermore, introducing difficulty levels is warranted, considering that the range of motion varies among patients and is based on different factors and their capability (also including different points in time during their individual rehabilitation). In this context, integrating intelligent algorithms capable of adapting puzzle-solving tasks and their difficulty to user needs would also be desirable. Additionally, there is currently no mechanism for providing patients with hints for solving tasks. This can diminish motivation and lead to the neglect of rehabilitation, impeding the game's intended therapeutic impact. Such mechanisms would be essential for further developing the serious game to maximize its effectiveness. Another aspect of gameplay that will be considered in future work, based on the evaluation results, is the creation of an inventory or another option to store objects. This inventory should be capable of storing and combining different objects and could also be used for additional smaller mini-games with specific movements included. In addition, future work will include a more extensive evaluation involving patients through an intervention study, which is expected to yield significant results. These results should encompass not only gameplay aspects but also the therapeutic outcomes of the intervention. This approach will provide a comprehensive understanding of both the effectiveness and the practical benefits of the serious game in a rehabilitation setting. In addition to including patients, other data (angular accelerations, changes in patterns of movement ranges, and amplitude of joint angles) from them should also be included. Ultimately, such a study would help validate the use of gaming technologies in enhancing patient recovery and improving quality of life. Furthermore, it is crucial to display specific information for therapists, including summaries of games played, performance metrics, and pain-scale evaluations. These elements should be considered for integration in future developments. Providing therapists with such detailed feedback will enable them to tailor rehabilitation sessions more effectively to individual patient needs. This approach will not only enhance the therapeutic process but also aid in monitoring patient progress more accurately and often. Incorporating these features in future work will undoubtedly improve the overall functionality and utility of therapeutic gaming applications. These aspects need to be planned and will be looked into in the near future.

Author Contributions: Conceptualization, R.B., C.H. and L.R.; methodology, R.B., C.A. and T.G.; software, C.H. and L.R.; validation, R.B., D.H., W.H. and T.G.; formal analysis, R.B., C.H. and L.R.; investigation, R.B., C.H. and L.R.; data curation, R.B.; writing—original draft preparation, R.B.; writing—review and editing, D.H., C.A., W.H. and T.G.; visualization, R.B., C.H. and L.R.; supervision, T.G. and R.B.; project administration, R.B. All authors have read and agreed to the published version of the manuscript.

Funding: Open Access Funding by TU Wien Bibliothek.

Institutional Review Board Statement: No patients were involved in this study. This study was conducted in compliance with good clinical practices and Austrian legislation on research and data protection in accordance with the Declaration of Helsinki.

Informed Consent Statement: Informed consent was obtained from all subjects involved in this study.

Data Availability Statement: Data available on request due to privacy restrictions. The raw data presented in this study are available on request from the corresponding author. The data are not publicly available due to follow up research and privacy of the participants.

Acknowledgments: First and foremost, we would like to thank all the people who participated. The authors acknowledge TU Wien Bibliothek for financial support through its Open Access Funding Programme for this article.

Conflicts of Interest: Author Werner Hoerner was employed by the company Human & Digital, author Dominik Hoelbling was employed by the company Research Industrial Systems Engineering (RISE). The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AR	Augmented Reality
COTS	Commercial Off The Shelf
UCD	User-Centered Design
CRPS	Complex Regional Pain Syndrome
DTM	Dart-Throwing Movement
HMD	Head-Mounted-Display
LMR	Leap Motion Controller
SUS	System Usability Scale
UES	User Engagement Scale
VR	Virtual Reality

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