Digital Rehabilitation Environments after Traumatic Hand Injuries or Limb Amputations

Dissertation

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Abstract

Rehabilitation after traumatic injuries or limb amputations often is a tedious, repetitive, and painful process, which can be supported by digital technologies in numerous ways. One of these technologies is digital media, which can be used to create versatile and interactive environments. As part of this dissertation, 3 software applications were conceived and developed around the topics of phantom limbs and the gamification of therapy with the purpose of supporting patients in their rehabilitation process. In addition to the specific requirements for each scenario, we focused on maximizing the user experience and suitability for daily use in a clinical or therapeutic setting.

The first application is CALA (Computer Assisted Limb Assessment), a digital tool for the visualization and documentation of phantom limbs and phantom sensations. In the present publication, a prototype of CALA was evaluated with therapists and patients regarding its usability and functional coverage and additional requirements for such a tool were collected. After the study was completed, a full version of CALA was developed based on the knowledge gained. In the second study, we developed StableHandVR, a "serious game" that was designed to support and motivate patients to perform exercises to regain hand and finger mobility after a traumatic injury. The aim of this study was the iterative development and evaluation of the game, which started with a prototype and ended with a revised full version. For the third study, PhantomAR was developed, a mixed reality application for the relief of phantom limb pain. While traditional mirror therapy alleviates phantom limb pain by mirroring the intact limb, PhantomAR augments a virtual limb onto the stump of the patient's residual limb. This enables the user to move around freely and to perform bimanual interactions with virtual objects. The present study investigated the clinical effectiveness of PhantomAR and its usability and suitability for everyday use.

The process of investigating, elaborating, and implementing the requirements did not only generate knowledge about the respective problems but also revealed hurdles for good usability. By combining the core components of the resulting applications, it is conceivable to cover a further application scenario: With customizable virtual phantom limbs, digital mirror therapy might become usable for patients for whom the illusion of traditional mirror therapy does not work due to a distorted phantom limb.

Kurzfassung

Die Rehabilitation nach traumatischen Verletzungen oder Amputationen von Gliedmaßen ist oft ein langwieriger, repetitiver und schmerzhafter Prozess, der durch digitale Technologien bereits auf vielfältige Art und Weise unterstützt wird. Eine dieser Technologien sind digitalen Medien, welche das Erschaffen von vielfältigen multimedialen und interaktiven Umgebungen ermöglichen. Im Rahmen dieser Dissertation wurden drei derartige Softwareanwendungen entwickelt und unter Zuhilfenahme wissenschaftlicher Methoden evaluiert. Die Anwendungen befassen sich mit den Themen Phantomglieder und Gamifizierung von Therapie und verfolgen den Zweck, Patienten in diesem Prozess zu unterstützen. Zusätzlich zu den spezifischen Anforderungen für die jeweilige Anwendung war unser Fokus darauf gerichtet, die Benutzerfreundlichkeit und Eignung für den täglichen Gebrauch in einem klinischen oder therapeutischen Umfeld zu maximieren.

Bei der ersten Anwendung handelt es sich um CALA (Computer Assisted Limb Assessment), ein digitales Werkzeug zur Visualisierung und Dokumentation von Phantomgliedern und Phantomempfindungen. In der vorliegenden Publikation wurde ein Prototyp von CALA mit Therapeuten und Patienten evaluiert, um Einblicke in die Benutzerfreundlichkeit und den Funktionsumfang zu erlangen. Außerdem wurden weitere Anforderungen für ein derartiges Tool gesammelt. Nach Abschluss der Studie wurde auf diesem Wissen basierend die Vollversion von CALA entwickelt. Im Rahmen der zweiten Studie wurde StableHandVR entwickelt, ein „Serious Game“ mit dem Zweck, Patienten bei der Wiedererlangung ihrer Hand- und Fingerbeweglichkeit nach einer traumatischen Verletzung zu unterstützen. Ziel der vorliegenden Studie war die iterative Entwicklung und Evaluierung des Spiels, beginnend mit einem Prototyp und resultierend in einer überarbeiteten Vollversion. Für die dritte Studie wurde PhantomAR entwickelt, eine Mixed-Reality-Anwendung zur Linderung von Phantomschmerzen. Während die traditionelle Spiegeltherapie Phantomschmerzen durch Spiegelung der intakten Gliedmaße lindert, wird bei PhantomAR eine virtuelle Gliedmaße auf den Stumpf des Patienten augmentiert. Dies ermöglicht ein freies Bewegen in der Umgebung sowie eine unabhängige beidhändige Interaktion mit virtuellen Objekten. Die vorliegende Studie untersuchte die klinische Wirksamkeit von PhantomAR sowie dessen Benutzerfreundlichkeit und Alltagstauglichkeit.

Das Sammeln und Ausarbeiten der Anforderungen und deren anschließende Um-

setzung für alle 3 Anwendungen brachte nicht nur viel Wissen um die jeweiligen Problemstellungen, sondern zeigte auch vorhandene Hürden für das Erreichen guter Benutzerfreundlichkeit auf. Durch Kombination der Kernkomponenten aus den drei resultierenden Anwendungen ist ein weiteres interessantes Anwendungsszenario denkbar: Durch individuell gestaltbare virtuelle Phantomglieder könnte digitale Spiegeltherapie für Patienten nutzbar gemacht werden, bei denen die Illusion der traditionellen Spiegeltherapie aufgrund eines als verzerrt empfundenen Phantoms nicht funktioniert.

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Acronyms

Chapter 1

List of Publications

1.1 Accepted Publications

1.1.1 Publication I: CALA

Title Visualizing the Unseen: Illustrating and Documenting Phantom Limb Sensations and Phantom Limb Pain with C.A.L.A. (Bressler *et al.*, 2022).

Journal Published in Frontiers in Rehabilitation Sciences, February 2022.

Summary CALA (Computer Assisted Limb Assessment) is a software tool for visualizing, documenting, and quantifying the body image of amputees who experience phantom limb sensations or phantom limb pain. This study reports on the evaluation of a prototype, which provided the basic functionality of CALA.

Significance of the Author's Contributions Michael Bressler extended the functionality and the user interface of the existing CALA prototype, mainly contributed to the generation of the self-developed survey and the semi-structured interview that were used for evaluating the prototype, contributed to data generation, and contributed significantly to the writing of the manuscript.

1.1.2 Publication II: StableHandVR

Title A Virtual Reality Serious Game for the Rehabilitation of Hand and Finger Function: Iterative Development and Suitability Study (Bressler *et al.*, 2024).

Journal Published in JMIR Serious Games, August 2024.

Summary StableHandVR is a serious game for regaining the mobility of the hand and fingers. It uses the Meta Quest 2, a low-cost immersive virtual reality display with integrated optical hand tracking to create an immersive gamified training environment for patients. In the study presented, the game was iteratively developed and evaluated in 3 distinct stages.

Significance of the Author's Contributions Michael Bressler developed the underlying Architecture of StableHandVR, contributed significantly to and supervised the further programming of the prototype and versions 1 and 2, contributed to the scientific ideas for evaluating the applications, in particular to the generation of a self-developed survey and the semi-structured interview, contributed to data generation, contributed significantly to the data analysis, contributed significantly to the data analysis, and contributed significantly to the writing of the manuscript.

1.2 Accepted Co-Authorships

1.2.1 Publication III: PhantomAR

Title PhantomAR: Gamified Mixed Reality System for Alleviating Phantom Limb Pain in Upper Limb Amputees – Design, Implementation, and Clinical Usability Evaluation (Prahm *et al.*, 2025).

Journal Published in Journal of NeuroEngineering and Rehabilitation, February 2025.

Summary PhantomAR is a digitally enhanced variant of traditional mirror therapy that uses a low-cost immersive mixed reality device, the Microsoft HoloLens 2, to augment the amputated limb of a patient onto their residual limb. The study reports on the evaluation of the system regarding its clinical efficacy of alleviating PLP and the general feasibility and usability.

Significance of the Author's Contributions Michael Bressler developed the underlying Architecture of PhantomAR, contributed significantly to and supervised the further programming of PhantomAR, contributed to the generation of scientific ideas for evaluating the usability of PhantomAR, contributed to data generation and analysis, and to the writing of the manuscript.

Chapter 2

Introduction

Rehabilitation can be a challenging process for patients. Exercises tend to be repetitive and can quickly become monotonous, which reduces engagement and motivation. Pain reactions can occur during or after the exercises and must be endured. Progress can move slowly, making it difficult for patients to observe improvement and stay motivated over the course of therapy. This does not only affect the patient's quality of life but also the duration and outcome of the rehabilitation process. The integration of digital technologies provides much potential to address these challenges and already offers solutions that significantly facilitate exercising or enhance the effectiveness of rehabilitation. Robotics and exoskeletons support motor recovery (Abbate *et al.*, 2023; Liu *et al.*, 2018). Smart prosthetics and orthotics behave almost naturally and can provide sensory feedback (Kulkarni *et al.*, 2024). Telerehabilitation overcomes geographical and physical barriers and enables patients to receive care in their own homes (Rothgangel *et al.*, 2017). Artificial Intelligence and Machine Learning enable personalized treatment, automated assessments and virtual assistance (Khalid *et al.*, 2024).

In this dissertation, the focus will be set on a specific application domain: digital media applications, which enable interactive and immersive scenarios that can range from realistic simulations to fictional environments and even tailor-made realities, e.g., with altered gravity. Application scenarios are exposure therapy and desensitization training, physical rehabilitation, or pain management. Digital media can further be used to create engaging games and interactive behavioral change apps that are designed with the purpose of supporting and keeping up the patient's motivation through the rehabilitation process (Kato, 2010).

2.1 Serious Games

The term *Serious Games* is often attributed to the book "Serious Games" (Abt, 1970), which describes the concept of games that are not designed primarily for entertainment. Instead, their main purpose is to educate, train, or to promote a

specific agenda, e.g., safety, health, or socially relevant topics such as environmental protection. However, the concept of serious games does not neglect the entertaining aspect of games; on the contrary, this part is essential to captivate and engage the user and to make serious games actually work (Engström and Backlund, 2021). The field of medicine has a long history of embracing game-based approaches to drive patient engagement and improve health outcomes. In the 1980s, video games started being used with patients and eventually evolved to the predominant format. In the last 15 years, the focus has shifted more and more towards tailor-made games for certain disease or disorder groups (Kato, 2010).

Constant advancements in consumer electronics have propelled this development as well as the increasingly simplified process of creating video games for various platforms and devices with game engines like Unity[1] or Unreal Engine[2]. Today, serious games for healthcare and rehabilitation cover a wide range of application domains. They are used in health education and prevention, e.g., for weight reduction (Liu *et al.*, 2022) or smoke-stop (Andrew *et al.*, 2023); in cognitive rehabilitation, e.g., as memory training for patients with dementia (Chang *et al.*, 2022); for the treatment of perceptual disorders, e.g., spatial neglect (Stammler *et al.*, 2023) or pusher syndrome (Wöhrstein *et al.*, 2024); in physical rehabilitation, e.g., for speech rehabilitation training after stroke (Bu *et al.*, 2022) or upper limb training for patients with multiple sclerosis (Kalron *et al.*, 2022); or as social and emotional skill training, e.g., for children with autism spectrum disorder (Terlouw *et al.*, 2021).

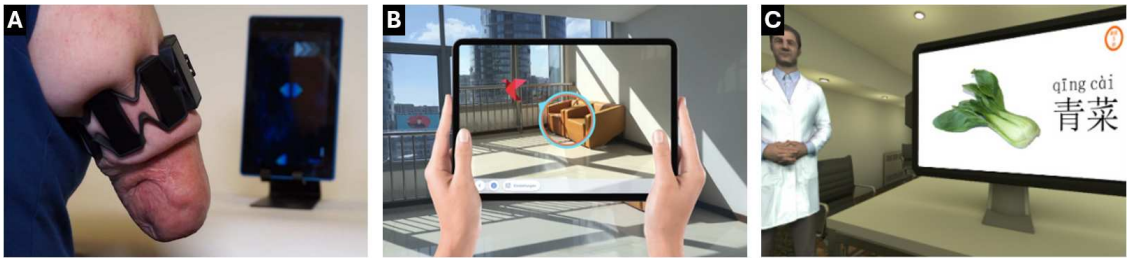

Figure 2.1: Tailor-made serious games for rehabilitation: **(A)** a rhythm game to train the myoelectric control of prostheses (from Prahm *et al.* (2019c), © 2019 IEEE); **(B)** following the bird as augmented reality treatment for spatial neglect (from Stammler *et al.* (2023), JMIR Serious Games, CC BY 4.0); **(C)** a virtual reality based oral expression therapy for patients with aphasia (from Bu *et al.* (2022), JMIR Serious Games, CC BY 4.0).

Today, the field of serious games is rapidly growing and a dynamic area of research. Some of the main trends are the management of chronic health conditions (e.g., asthma or diabetes), the promotion of healthy behavior, a shift towards digital mobile platforms, an increased use of immersive technologies such as virtual reality

[1] `https://www.unity.com` (Access: 10th of July 2025)
[2] `https://www.unrealengine.com` (Access: 10th of July 2025)

(VR), and an increased need to understand the underlying mechanisms of effective game mechanics and design elements (Damaševičius *et al.*, 2023).

2.1.1 Gamification

Gamification is defined as the application of design elements that are typically used in gameplay to other, non-game related contexts. The term emerged in 2008, and relevant research started around 2010. The idea is to isolate the addictive mechanics of a game and to put them into another digital technology, which will then become addictive too (Cugelman, 2013; Krath *et al.*, 2021). Commonly used game mechanics are points & badges, quests and challenges, storytelling, virtual rewards, personalization, social connections, feedback and coaching, immersive technologies and game environments (Damaševičius *et al.*, 2023). However, one of the biggest misconceptions is to think that the sole implementation of such mechanics and technologies will lead to a more engaging experience. Without certain persuasive ingredients, the mere mechanism is not necessarily persuasive. It is therefore important to consider the linkage of the game mechanics to behavior change strategies and to ensure, that the mechanics satisfy these strategies (Cugelman, 2013). The most common theoretical foundations for engagement and motivation are Self-determination theory, flow theory, and goal setting (Krath *et al.*, 2021). Self-determination theory defines 3 basic needs which must be fulfilled to ensure motivation (Deci and Ryan, 1985), namely autonomy, competence and relatedness. Flow theory aims for deep focus and immersion in an activity by ensuring an adequate level of challenge, clear feedback, and the presence of intrinsic motivation through an enjoyable task (Csikszentmihalyi, 1975). The idea behind Goal Setting is that setting specific and challenging but attainable goals improves motivation and performance (Locke, 1968). Different personality types cause different preferences amongst players and how they experience satisfaction in games. While the *philanthropist* is motivated by purpose, the *free spirit* likes to explore; the *achiever* seeks for progress and mastery, and the *player* is motivated to earn points and to top the leaderboard. When designing game patterns, it should therefore be ensured that such different play styles are supported (Tondello *et al.*, 2016).

2.1.2 Generating Engagement

Since rehabilitation processes tend to take time, possibly many months, keeping up motivation can pose an additional challenge for game design. In current literature there is little design knowledge provided on how long-term engagement can be addressed, which exceeds the often-used 3-month evaluation time span. Considerations towards long-term engagement are, e.g., a focus on personalized and individual experiences by offering ways of choice and self-determination or the sup-

port of intrinsic motivation by showing health-related progress. A focus on mobile platforms like smartphones enables individual use and tight integration in everyday habits and routines (Kayali *et al.*, 2018).

To engage patients for particularly tedious tasks, e.g., the regular entry of health data, it can be beneficial to use highly manipulative design patterns such as those developed for monetizing online games. In a health-related context, *Grinding* must be mentioned, which aims to make the player perform the same task over and over just to gain levels and unlock new playable content (Achterbosch *et al.*, 2008). Another design pattern is *Playing by Appointment*, which requires the player to play at specific times that are defined by the game (e.g., every Sunday). Rather than rewarding the player for fulfilling the task, the player gets penalized if they fail to do so, e.g., if supplies spoil or the harvest withers (Zagal *et al.*, 2013). This raises the question whether it is unethical to use such psychologically manipulative design techniques. Design patterns that happen without the player's consent and cause negative experiences that are against the player's best interest can be considered as *dark patterns*. However, the "darkness" of such a pattern is strongly dependent on the context in which it is used. If the player is literate enough to see through the manipulation, it might be acceptable to use the pattern. If the pattern does not support the player's preferred play style, it might still become dark (Zagal *et al.*, 2013).

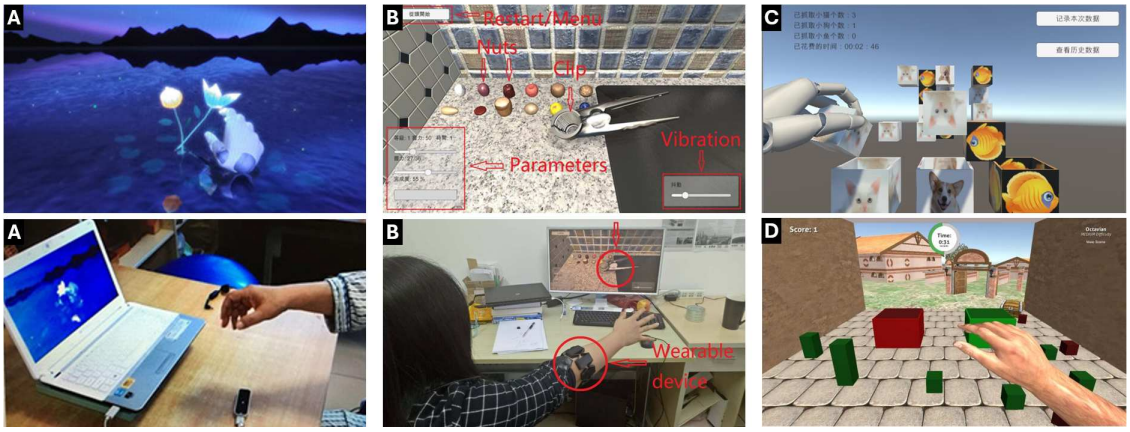

Figure 2.2: Examples of gamified hand and finger rehabilitation presented in literature rather focus on the technical feasibility and contain limited concepts for player engagement: **(A)** picking flower petals using hand tracking with the LeapMotion controller (modified from Wang *et al.* (2017), © 2017 Neural Regeneration Research), **(B)** cracking nuts through muscle contraction measured with the myoelectric bracelet Thalmic Labs Myo Armband (modified from Yang *et al.* (2017), © 2017 IEEE), or **(C** and **D)** grasping and collecting objects in virtual reality using hand tracking with the LeapMotion controller (C from Tang *et al.* (2017) and D from Postolache *et al.* (2017), both © 2017 IEEE).

While there are definitely ways and means of making even tedious tasks appealing to players, it is noticeable that many of the applications for limb rehabilitation that are presented in literature focus on technical feasibility and have limited concepts for player engagement. They rely on competitive game elements such as point systems (see Fig. 2.2) and leaderboards or contain no gamification elements at all. While such competitive mechanisms affect extrinsic motivation, they have little effect on intrinsic motivation and can even create frustration if the challenge level is not adequate (Mekler *et al.*, 2017). These approaches may be sufficient for technical feasibility studies, but their minimalistic design is only marginally usable to evaluate the actual suitability of such a system for the respective use case and might furthermore even impair the user experience.

2.2 Rehabilitation in Alternative Realities

The use of digital media enables the creation of virtual scenarios that can be explored and interacted with, and highly immersive VR systems aim to maximize the feeling of being "physically present" in these virtual worlds. The high degree of immersion promises to enable a more engaging experience and performance, thus enhancing the positive effects of gamification (Bui *et al.*, 2021; Sanchez-Vives and Slater, 2005). Moreover, high-immersion VR systems enable the user to respond consciously and subconsciously in a more realistic way to the virtual stimuli and might even induce physiological reactions, e.g., the alleviation of pain. An often mentioned use case is the application of VR in burn victims, who are placed in a virtual winter world during bandage change (Hoffman *et al.*, 2020; Kato, 2010; Wittkopf *et al.*, 2020). The term "virtual reality" in the context of rehabilitation is often misused in scientific papers and referred to as any type of digital system. Therefore, many „VR" systems presented in literature use a standard 2D monitor in front of which the patient is placed, and only create a reduced degree of immersion (Tieri *et al.*, 2018). In contrast, "real" VR surrounds the user, which can be achieved by surrounding translucent walls, onto which images are projected from the outside (Cruz-Neira *et al.*, 1993) or more conveniently by wearing a head mounted display (HMD). By tracking the position and gaze of the head in real-time, the user can look and move around freely within the virtual environment and experience it from a first-person perspective. The degree of immersion can be further increased by a wide field-of-view, stereoscopic vision, spatial sound and an overall low latency of the system (Harth *et al.*, 2018).

2.2.1 Physical Activities in Virtual Reality

While the senses of sight and hearing can be played well with an HMD, the physical interaction with the virtual world is not as simple to establish. Nevertheless, body- or limb-involving activities often play a fundamental role in rehabilitation, and interaction is a key factor for high immersion (Harth *et al.*, 2018). Digital rehabilitation systems presented in literature use a wide range of input systems that involve physical action beyond the use of a controller. As long as the user stays in place, full body tracking can be established with affordable consumer electronics such as the Nintendo Wii (Standen *et al.*, 2017) or the Microsoft Kinect sensor (Annapureddy *et al.*, 2022). Since walking in VR is limited by the physical space in which the simulation takes place, the simulation of unlimited walking or running requires a treadmill (Soon *et al.*, 2023). For lower limb amputees, a pedal crank can be used instead to simulate (bi-)pedal activities (Ambron *et al.*, 2021). If only certain limbs need to be tracked, inertial measurement unit (IMU) can be placed directly on the respective body parts and measure their orientation in space (Ambron *et al.*, 2018). Such IMU sensors can be built small, work fully wireless, and are not affected by occlusion like optical tracking systems. Tracking the hand and fingers and transferring them into VR enables the user to use them "naturally", and will likely create the highest possible degree of immersion concerning interaction (Harth *et al.*, 2018). However, most rehabilitation games that target the hand and fingers make use of the touchscreen of tablets or smartphones (Koutsiana *et al.*, 2020), which provides only limited possibilities for interaction. The most accurate tracking of the hand and fingers can be achieved with data gloves that are eventually equipped with IMUs (da Silva Cameirão *et al.*, 2011; Gabyzon *et al.*, 2016) or with exoskeletons (Liu *et al.*, 2018). A hands-free but less accurate alternative is marker-less optical tracking, either with an external setup of cameras or with a device that can be mounted directly onto the HMD, e.g., the Leap Motion Controller (Postolache *et al.*, 2017; Tang *et al.*, 2017) as seen in Figure 2.2. By now, standalone HMDs with integrated hand tracking, such as the Meta (formerly Oculus) Quest series[3] (Pereira *et al.*, 2020) or the ByteDance Pico 4[4] require no additional devices but only the HMD and thus provide the easiest handling and highest usability. If the hands are not available as input devices, the most common alternative input are voice commands, followed by eye and head gaze (Monteiro *et al.*, 2021). A further option is the use of electromyography (EMG) signals that are generated by muscle contractions (Akbulut *et al.*, 2019; Prahm *et al.*, 2019b), and commonly used for the myoelectric control of prostheses (see Fig. 2.2).

[3] `https://www.meta.com/quest/` (Access: 10th of July 2025)
[4] `https://www.picoxr.com` (Access: 10th of July 2025)

2.2.2 Affordable Virtual Reality Technology

The technological progress of immersive and affordable VR systems has been tremendous in the last 15 years. In 2010, HMD devices were solely wearable screens and had to be connected to a computer, which generated the images for each eye. An infrared-optical pose-tracking system could be used to capture the position and gaze of the HMD in real-time with wall-mounted and shutter-synchronized cameras. Infrared filters and reflective tracking targets (see Fig. 2.3) had to be mounted on the HMD and other objects of interest (Pintaric and Kaufmann, 2007). The setup of such a system was elaborate and the system itself rather immobile, and the user experience was further impaired by a relatively small field-of-view of the HMD display, similarly shaped as sunglasses, by cables tethering the user or through backpacks containing power supply and other additional hardware (Sanchez-Vives and Slater, 2005). In 2018, the Oculus GO, was released as the first standalone VR HMD, meaning that no additional hardware was required to operate the system. This HMD could track the gaze of the head but not its position, meaning that the user could look around in a virtual world but was not able to move. In 2019, the former Oculus (and now Meta) Quest HMD closed this gap and further introduced an integrated optical hand and finger tracking system that did not require external cameras or other devices, no markers and no calibration. Along with the improvement of the hardware there has been a huge drop in price. While the cost of an HMD was US $35,000 in 2013 and the total system cost could easily exceed $100,000, HMD costs dropped to US $600 in 2016 when the Oculus Rift was released (Hoffman *et al.*, 2020). Today in 2025, the total system cost for a standalone HMD device with hand tracking is at US $300 (Meta Quest 3S). The low price and the easy and quick setup render this technology widely accessible and suitable for everyday use.

Instead of a purely virtual environment, it might be advantageous for certain use cases to blend the virtual world with the real environment and real objects. The spectrum of mixed reality (MR) is theoretically continuous and its distinction from augmented reality (AR) is not standardized and often confused in literature. Per definition, MR refers to the entire spectrum of blends, however, MR is often defined as a 'stronger' version of AR. While AR only enriches the real environment with virtual objects, MR enables the interaction between both worlds. The stronger the physical and the virtual world are linked, the more knowledge about the physical world must be possessed by such a system, e.g., spatial information (Milgram and Kishino, 1994; Skarbez *et al.*, 2021), and due to the higher technical requirements, MR displays are more expensive than VR HMDs. A standalone MR device comparable to the Meta Quest 2 is the Microsoft HoloLens 2[5], which was released in

[5] `https://learn.microsoft.com/hololens/` (Access: 10th of July 2025). The HoloLens 2 is no longer distributed.

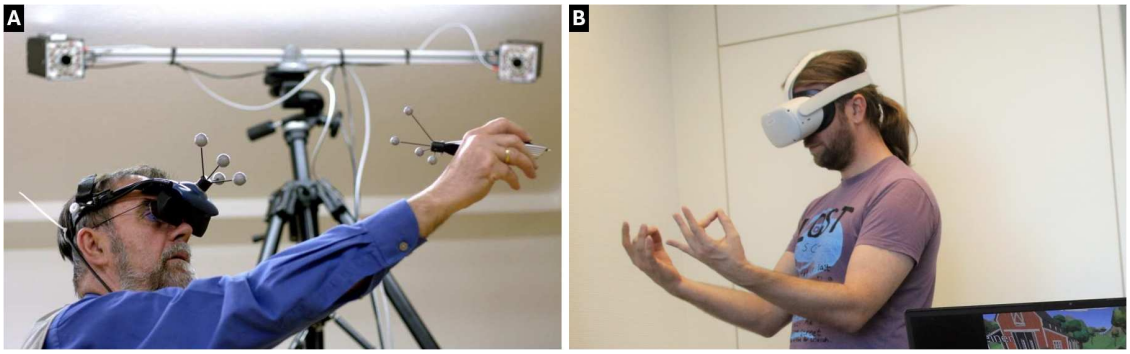

Figure 2.3: The technological progress of low-cost immersive virtual reality systems illustrated by comparing 2 systems from 2007 and 2023: **(A)** The low-cost IO-Tracker tracking system in combination with a cable-bound head mounted display, linked to a powerful computer has a total system cost of approx. US $15,000 to $20,000 (from Pintaric and Kaufmann (2007), © 2007 IEEE). **(B)** Meta Quest 2, a standalone head mounted display with integrated optical hand tracking was released in 2020 with a price of US $300.

2019 with a price of US $3,500 at market launch. The device uses infrared cameras and a time-of-flight depth sensor to provide a constantly updated spatial model of the environment. The resulting 3D mesh can then be used, e.g., to place virtual objects on real surfaces such as tables, drop them down on the floor or to let them be occluded by real objects. Regardless of the blend, the immersive first-person perspective of a HMD can induce a strong feeling of embodiment over a virtual body or limb, which forms a promising basis for a variety of therapeutic scenarios. For example, the patient can be exposed to the sight of their "own" body, while it is performing pre-programmed motor exercises (Tieri *et al.*, 2018), a specific representation of the limbs can have pain-relieving effects (Osumi *et al.*, 2019), and the visualization of body images can be used for the treatment of body perception disorders or body image disturbance (Alcañiz *et al.*, 2000).

2.3 Phantom Limbs and Pain

Following limb amputations, 90-98% of those affected experience their lost limb as still being present, a phenomenon known as phantom limb sensation (PLS). While PLS itself may not be inherently unpleasant, up to 80% of amputees also experience phantom limb pain (PLP), which can manifest as painful sensation including cramping, burning, or shooting pain (see Fig. 2.4). In some cases, the phantom limb may even be perceived as fixed in a contorted position or retracted into the body (Flor, 2002). PLP typically occurs immediately or within a week after the amputation, but the onset can also be delayed by months or even years. The

duration of PLP also varies greatly and in some individuals can become chronic and lasting up to 40 years. The quality of life for those suffering from PLP is significantly impaired and can lead to sleep disturbances, depression, anxiety, and difficulties with physical rehabilitation (Kulkarni and Richardson, 2017; Luo and Anderson, 2016; Ramachandran, 1998).

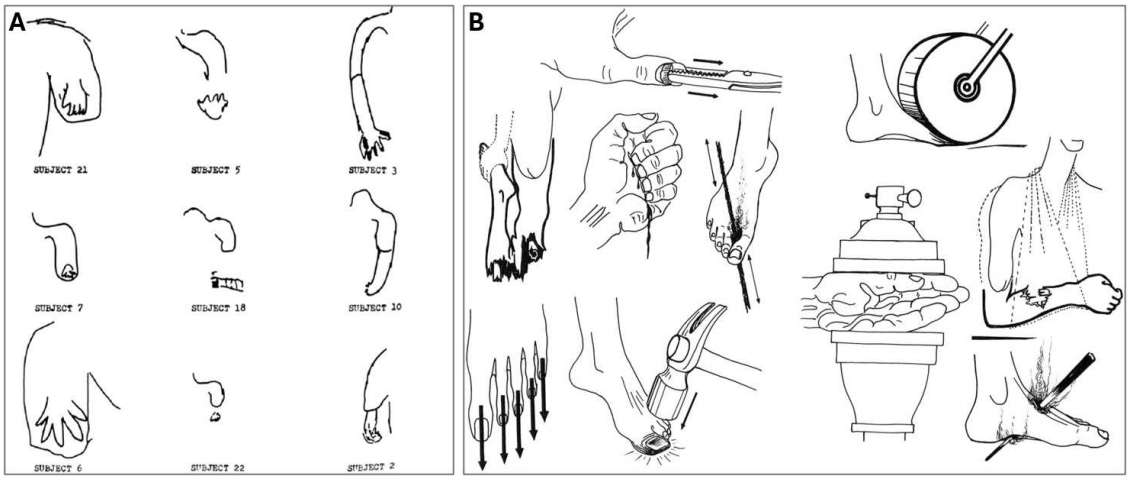

Figure 2.4: (A) Patient drawings of their phantom limbs, showing redacted and extended limbs and limbs with gaps. **(B)** Illustrations of phantom limb pain using metaphors. Both from Schott (2014), Brain, by permission of Oxford University Press. License number: 6053020604608.

2.3.1 Explaining Theories

The underlying mechanics of PLP are yet not understood in their full complexity but over the last 25 years, explanatory theories emerged and partly built upon each other. The concept of a *neuromatrix*, conceived by Melzack (2001), describes pain as complex activity patterns in the brain instead of direct reactions to nociceptive stimuli. These patterns emerge from interactions between cognitive, emotion-related, motor, and sensory networks in the brain. After an amputation, the proprioceptive memory of all body parts is still intact and expects information from the missing limb, which generates a feeling of presence. This contradiction to the visual absence of the limb and the lack of peripheral signals can activate pain memory programs (Melzack, 2001). In 2002, Herta Flor could show a link between PLP and cortical reorganization in the brain, which happened due to the lack of sensory input, and caused the affected parts of the sensory cortex to start processing signals from adjacent parts (Flor, 2002). The theory of stochastic entanglement adds further explanation to the linkage between the absence of the limb and the activation of pain patterns, which can first occur even years after an amputation. Contradictory

to Melzack, PLP is not only driven by the central nervous system (CNS) but also contributed to by the peripheral nervous system (PNS). According to Hebb's Law, the recurring simultaneous stochastic firing of neurons from the unconnected peripheral nerve together with neurons that are part of a network for pain perception could eventually establish a connection (Ortiz-Catalan, 2018). The intense use of a myoelectric prosthesis seems to have a positive influence not only on the reduction of PLP, but also on less cortical reorganization (Flor, 2002). This indicates that we must prevent or unlearn these maladaptive connections to sustainably alleviate PLP. An early treatment is therefore essential for the prevention and alleviation of PLP (Nees *et al.*, 2024).

2.3.2 Visual Illusion as a Form of Therapy

Current approaches for the treatment of PLP can be divided into pharmacological, surgical, and non-invasive approaches. While pharmacological treatments include the use of strong drugs such as antidepressants, ketamine, opioids, or local anesthetics, they usually only achieve a partial reduction in pain intensity while patients must endure the side effects of the medication. Surgical approaches on the other hand are not applicable in all cases and target the reduction of residual limb pain (RLP), which, however, can be a risk factor for the development of PLP. Possible surgical interventions are stump revision, neurectomy[6] or targeted muscle or sensor reinnervation, which prevents the development of neuromas by re-connecting the loose nerve end and can further help to improve the myoelectric control of prostheses and the perception of sensory feedback, which both can reduce PLP (Kaur and Guan, 2018).

The variety of non-invasive approaches presented in literature ranges from rather experimental methods such as sensory stimulation of the cheeks (Ichinose *et al.*, 2017) or the inner ear (Aranda-Moreno *et al.*, 2019) to more common approaches such as sensory discrimination training, mirror therapy or graded motor imagery. In mirror therapy, the intact limb is reflected by a mirror and tricks the brain into "seeing" the missing limb, which can alleviate PLP (Ramachandran, 1998). Graded motor imagery is a further developed form of mirror therapy, which aims to reorganize the maladaptive neuronal adaptions in the brain by gradually training the inner depiction of a deliberately moved phantom limb (Hinkel, 2017; Rierola-Fochs *et al.*, 2021). This combination of mirror-induced illusion and motor imagery can activate the primary motor cortex (Bello *et al.*, 2020). To keep the illusion intact, the patient must be seated in front of the mirror and maintain a certain posture and gaze. Also, no bimanual action or interactions with objects can be simulated and it is difficult to recreate real-world scenarios. The use of digital media technologies

[6] The resection of a neuroma, which might develop from a disconnected nerve end.

promises to overcome these limitations to a certain extent. In literature, several examples can be found that aim to transfer mirror therapy into a digital environment (see Fig. 2.5). This ranges from the mere depiction of the missing limb, e.g., mirrored in a screen that has been transformed into an augmenting mirror (Ortiz-Catalan *et al.*, 2016) or in VR using a first person perspective (Annapureddy *et al.*, 2022) to more complex setups such as VR mirror therapy combined with motor imagery and the use of exoskeletons to support the movements of the patient (Abbate *et al.*, 2023). Multisensory stimulation can further increase the degree of immersion, as demonstrated in a work where vibro-tactile feedback was induced in a VR setting to indicate the surf touching the simulated limb of the patient, who was sitting in a chair at the beach (Risso *et al.*, 2022). The efficiency of mirror therapy, graded motor imagery and virtual equivalences seems to be similar, but the general evidence of these therapies to effectively alleviate PLP is limited. This is mainly due to a low number of studies, many of which are case or pilot studies or of poor methodological quality (Herrador Colmenero *et al.*, 2018; Wittkopf *et al.*, 2019).

2.3.3 The Virtualization of Phantom Limbs

While it is still not fully understood, why mirror therapy is not equally effective for all patients, the use of AR/VR technologies might be an approach to make this therapy form more usable, especially for patients who currently experience no effect through conventional mirror therapy (Ortiz-Catalan *et al.*, 2016). Furthermore, digital variants of mirror therapy enable to use altered representations of the missing limb, e.g., in a frozen cave or covered with iron armor, which is relevant for maximizing the efficiency of pain reduction (Wittkopf *et al.*, 2019). An altered limb representation might be particularly effective for the visualization of distorted phantom limbs, where the mere illusion of a mirrored limb may fail. A matching visual representation of the perceived phantom limb could increase the sense of ownership as well as associated neurophysiological effects (Rothgangel and Bekrater-Bodmann, 2019).

To create a visual representation, the characteristics of the phantom limb must somehow be captured. However, there is no standard for the documentation of phantom limbs, which is often done with pain questionnaires that focus on the occurrence and intensity of pain and its impact on the patient's quality of life. Literature provides several examples for the visualization of disturbed body images, of which many target obesity and eating disorders (Alcañiz *et al.*, 2000; Ferrer-Garcia *et al.*, 2013; Letosa-Porta *et al.*, 2005). We found one publication which presented a tool to visualize the distorted body image of complex regional pain syndrome (CRPS) patients (Turton *et al.*, 2013) and finally also an example for the visualization of phantom limbs (Rogers *et al.*, 2016). This application facilitates the process of applying the perceived position of phantom limbs on a 3D model by

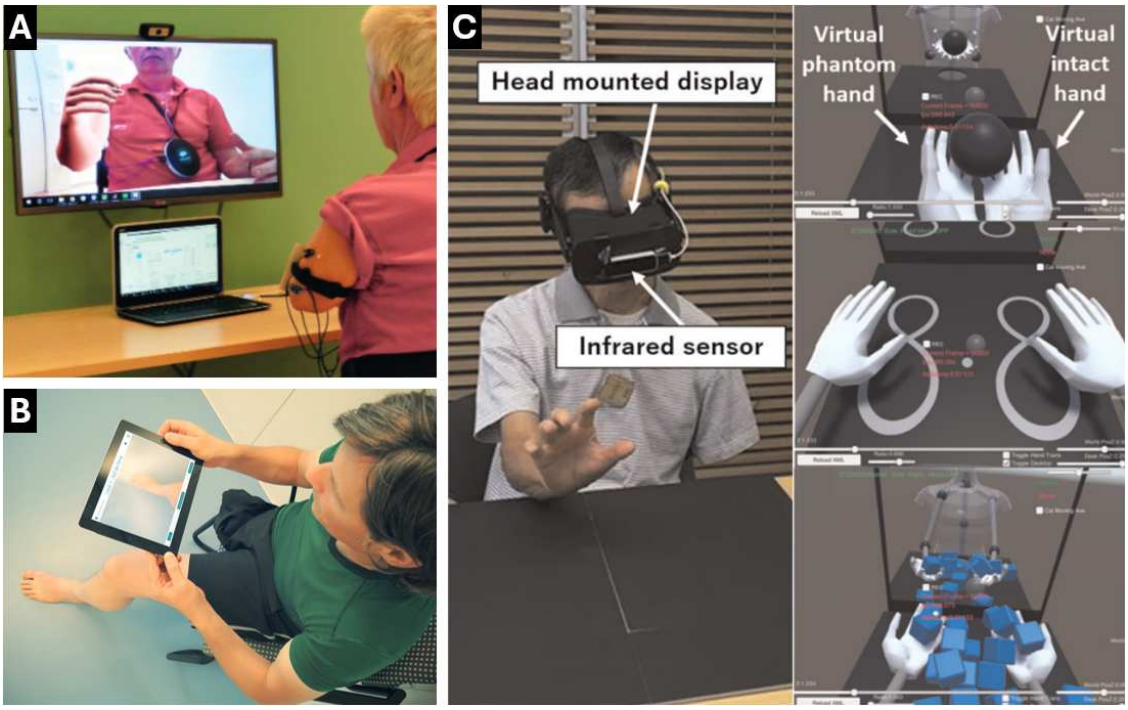

Figure 2.5: Three examples of digitally enhanced mirror therapy: **(A)** an augmented mirror visualizes the missing limb (modified from Ortiz-Catalan *et al.* (2016), The Lancet, by permission of Elsevir. License number: 6053021375066), **(B)** tablet based mirror therapy uses the camera of the tablet to augment the missing limb (from Rothgangel *et al.* (2017), JMIR Rehabilitation and Assistive Technologies, CC BY 2.0), and **(C)** a virtual-reality based approach visualizes the missing limb by mirroring the movements of the healthy side (modified from Osumi *et al.* (2019), Pain Medicine, by permission of Oxford University Press. License number: 6053030075750).

tracking the posture of a healthy hand with the Leap Motion Controller[7]. However, the respective publication primarily focused on the technical implementation of a movable digital arm and hand model and did not target other aspects of the phantom limb, such as pain or a prolonged or shortened limb. To illustrate a phantom limb as it is perceived by the patient, they would still have to guide an artist or rely on drawing it themselves (Schott, 2014).

2.4 Objectives

This dissertation focuses on the development of 3 tailor-made applications that arose around the topics of phantom limbs and gamification and were conceived and evaluated in close collaboration with physiotherapists, doctors, and patients. The scientific interest of the studies presented did not aim for the development of innovative technologies, but focused on the investigation and elaboration of requirements, their practical implementation by using established technologies and techniques, and their subsequent evaluation with scientific methods. An overarching goal for the development of all 3 applications was to aim for applicability in a clinical or therapeutic context. The applications should be cost-effective, mobile and user friendly, provide a quick and robust setup, and a clear and easy-to-use user interface. The respective objectives for the individual applications are listed as follows:

CALA Common documentation methods for PLS and PLP and the lack of options to visualize them make it difficult to grasp these phenomena in their entirety. CALA is a digital tool that aims to overcome these shortcomings. The goal of the presented study was to evaluate an existing prototype of CALA with therapists and patients regarding its acceptance, usability, and functional range. Furthermore, the study aimed to investigate the requirements for such a documentation tool to be used in a clinical or therapeutic context and the required functional range for it to sufficiently capture and visualize the perceived body image of amputees.

StableHandVR With the release of Oculus Quest in 2019, an extremely cost-effective immersive VR system with integrated optical hand tracking became available. Based on this technology, we developed StableHandVR, a serious immersive VR game for the rehabilitation of hand and finger mobility. The goal of the presented study was the iterative development and evaluation of the game, which aimed to create an engaging environment that would engage patients for a therapy period of 2 weeks. The evaluation was performed with able-bodied participants and

[7] `https://www.ultraleap.com` (Access: 10th of July 2025)

inpatients with an impaired hand function, and concerned the overall usability of the system, its suitability for patients with impaired hand function in particular, and its capability to effectively motivate the patients.

PhantomAR Since traditional mirror therapy is limited to unilateral and seated movements, we developed PhantomAR, a mobile assistive MR therapy tool for the standalone HMD Microsoft HoloLens 2, to overcome these limitations. PhantomAR enables the user to experience an augmented virtual hand from a first-person perspective in a freely explorable environment, and to bi-manually interact with virtual objects. The primary goal of the study was to evaluate the overall usability of the system and its efficacy in alleviating PLP. The study furthermore investigated the impact of different limb representations on the sense of embodiment and explored a potential link between skin temperature and PLP.

Chapter 3

CALA

CALA is intended as a digital tool that supports the process of visualizing, documenting, and quantifying phantom limbs and PLP in a therapeutic setting. The tool's functional scope should cover the most common appearances of phantom limbs, and its interface should be suitable for the use in everyday clinical practice. An early prototype of CALA had been developed for a previous study (Prahm *et al.*, 2019a) as a modified version of the open-source character modelling tool MakeHuman[1], and incorporated self-developed plugins for the 3D modelling tool Blender[2]. For the present study, the prototype was extended to cover lower limbs, and to provide more detail in capturing the posture and shape of the phantom limb. Additionally, the user interface of this early prototype was refactored towards a more streamlined and user-friendly form. Finally, the prototype provided the following functionality: (1) Adjusting the appearance of an avatar in terms of sex, age and physical constitution, (2) Measuring the patient's body and transferring the measurements to the avatar (3) adjusting the position and (4) the shape of the phantom limb, (5) drawing pain and cramps on the avatar and (6) quantifying the created body image (see Figure 6). The aim of this study was to evaluate the improved prototype with therapists and amputees to gather more requirements for the use of such a tool in practice. After the study was conducted, the full version of CALA was developed from-scratch with the Unity game engine.

Methods For the evaluation by therapists, all participants received an introduction to the use of the prototype and subsequently had to document 2 fictional cases of PLS and PLP that were handed out in written form. During the documentation process, the participants were observed and received assistance if required, and after completing both cases, they were questioned with the System Usability Scale (SUS) (Brooke, 1996), a self-developed survey and semi-structured interviews regarding the acceptance and usability of the application as well as its functional scope. Additionally, the prototype was evaluated with amputees with at least one

[1] `https://static.makehumancommunity.org` (Access: 10^{th} of July 2025)
[2] `https://www.blender.org` (Access: 10^{th} of July 2025)

Figure 3.1: **(A)** A patient and a therapist are modeling the patient's phantom limb with the CALA prototype. **(B)** An avatar could be adjusted, and the shape of the phantom limb could be modified. **(C)** A Blender plugin was used to adjust the phantom limb's position. **(D)** A further plugin enabled painting pain and cramps directly on the avatar.

limb amputation. The documentation was performed by the investigator, while the participant observed the resulting body image and intervened to correct if necessary. Subsequently, all participants were queried with the Short-Form McGill Pain Questionnaire (SF-MPQ) (Melzack, 1987) regarding their PLP, and with a self-developed survey and semi-structured interview to evaluate the functional coverage and the accuracy of the visualized body image.

3.1 Results and Discussion

The evaluation by therapists and other healthcare professionals (19 physical therapists, 9 occupational therapists, 2 orthopedic technicians and 3 medical staff; in the following referred to as therapists), took place with 33 participants with an age range of 25-58 and a mean age of 41 years. The evaluation with amputees was conducted with 22 individuals, of whom 17 were experiencing PLP. Of these, 5 amputees stated that they sensed a deformed phantom limb and 5 felt their phantom limb in a twisted position. 13 amputees were experiencing RLP.

3.1.1 Functional Coverage of the Prototype

The functions of the prototype were all rated high by the therapists; however, a tendency was visible towards higher scores for the options to visualize pain, shape, and position of the phantom limb while the options to quantify pain and shape received lower scores (see Fig. 3.2). In the semi-structured interviews, we asked the therapists about missing functions of the prototype, and most mentioned were the documentation of pain qualities (7 mentions), sensibility (7) and temporal aspects of pain (4). Further mentioned were pain triggers, influencing factors of pain (e.g., medication), the distinction between RPL and PLP, the sense of voluntary or involuntary movements of the phantom, and whether a prosthesis was worn. The 17 amputees with PLS were asked whether the prototype could map all aspects of their perceived body image, and 9 of the amputees answered with "Yes". Rated on a 1-5 Likert scale (1="very inaccurate", 5="very accurate"), the representation of the body image was rated with a mean score of 4.3 (SD .8) and the representation of the phantom limb with 4.6 (SD .7).

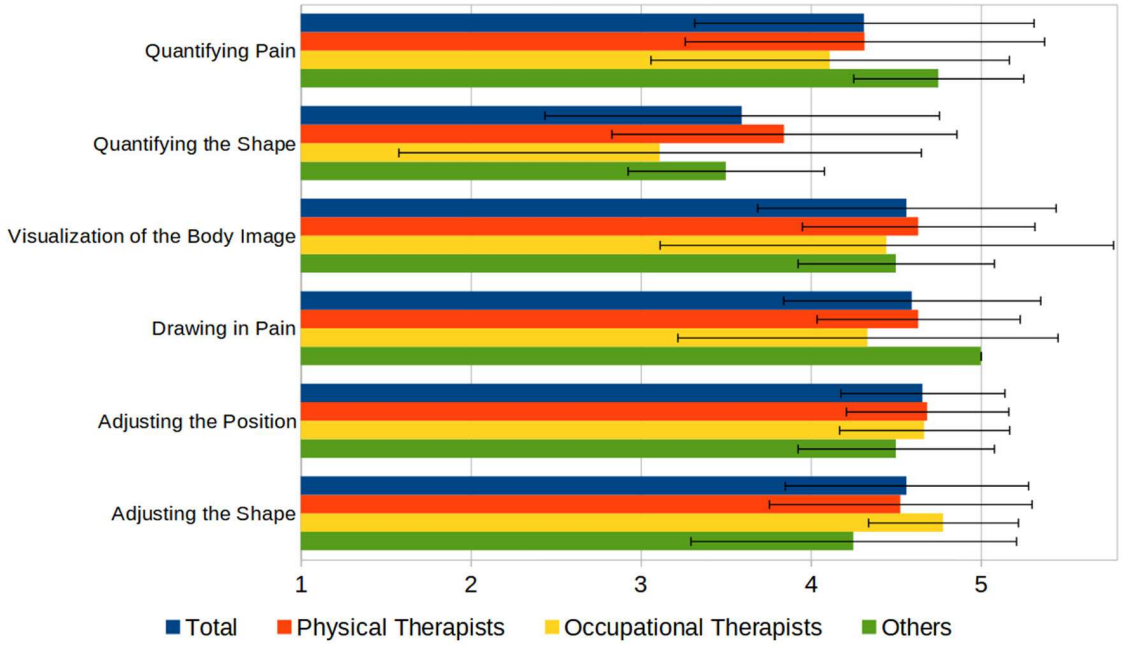

Figure 3.2: Therapists had to rate the usefulness of the functions provided by the CALA prototype on a 1-5 Likert scale (1="not useful", 5="very useful"). The chart shows the mean scores and SD. From Bressler *et al.* (2022), Frontiers in Rehabilitation Sciences, CC BY 4.0.

In the semi-structured interview, we asked about aspects of their PLS that were missing in the prototype, and most mentioned were pain qualities (8), the absence of the missing limb due to a fully intact body (4) and the change of pain over

time (3). Further mentioned were the progression of the pain sensation (spatial or regarding the qualities) and external influences, e.g., weather change. The 5 amputees, who perceived their phantom limb as twisted or altered in shape had to rate the accuracy of the mapped posture and shape of the limb as well. For both aspects, 4 out of 5 amputees answered with "Yes" to the question, if everything could be mapped, and rated the accuracy of the shape with 4.6 (SD .55) and the posture with 4.4 (SD .55). In the semi-structured interviews, the amputees also mentioned the lack of an option to move or deform individual fingers or to define anatomically impossible postures (e.g., an overextension of the knee $> 150°$).

3.1.2 Visualization of the Body Image

The importance of customizing the avatar in terms of weight, age and gender was rated low by therapists as well as by amputees. We observed that the existing options would quickly become insufficient for amputees who liked the idea of customizing the avatar in more detail, but we think that it is not conducive to the overall purpose of CALA. Although the accuracy of the body image and the phantom limb were rated high by the amputees, the missing depiction of the amputated limb, which was visualized as being still intact, was considered a major error in the representation. A visual distinction between phantom limb and residual limb could not only rectify the visualized body image but would also help to distinguish programmatically between PLS and RLP drawn on the avatar, since both, by definition, only occur on the phantom respectively on the residual limb (Flor, 2002). Another missing aspect in the visual representation was the perceived "presence" of the phantom limb, which usually fades faster in the proximal parts, while more distal parts such as fingers remain present for longer (Flor, 2002). This aspect could be visualized with different shades of transparency that are drawn directly on the avatar (see Fig. 3.3). Regarding PLS, half of the amputees stated that not all aspects could be mapped. The perceived position and deformation was most detailed in the fingers, which can be explained with their strong representation in the sensory cortex (Nakamura *et al.*, 1998). Therefore, it seems reasonable to extend the functional range of the prototype to individually adjust the length, thickness, and position of single finger phalanges. Since the toes usually are less strongly represented in the cortex, adjusting individual toes as a whole might be sufficient. Naturally, it would be appealing to enable the depiction of the phantom limb in even greater detail, e.g., toes, which feel rolled up like the lid of a sardine tin as described by one amputee. However, a line must be drawn here, primarily in favor of a standardized documentation process. After all, 4 out of 5 deformations and postures could be mapped accurately.

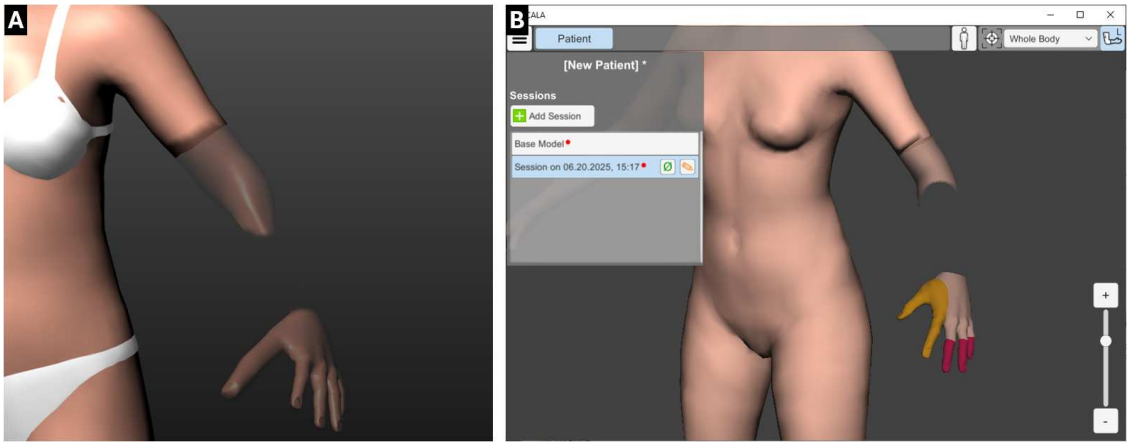

Figure 3.3: A comparison of **(A)** the conceptualized visualization of a phantom limb in CALA, based on the outcomes of the prototype evaluation (from Bressler *et al.* (2022), Frontiers in Rehabilitation Sciences, CC BY 4.0) and **(B)** the actual implementation in the current full version (version 0.94.2).

3.1.3 Documentation of the Body Image

When asked about their most frequently used documentation methods to assess and monitor PLS, PLP and an altered body image over the course of therapy, most therapists stated that they use a handwritten and self-defined form. Additionally, 45% used 2D body charts to draw in pain and 27% used validated questionnaires for their documentation. PLP and RLP were rated as the most important aspects in a therapeutic finding, followed by sensitivity and muscle tension disorder, while the posture and shape of the phantom limb were considered noticeably less important. This correlates with the semi-structured interviews, where therapists stated that pain - or more generally speaking - any discomfort and reduced quality of life are the main targets of PLP-related therapy and should therefore be considered most important. The documentation of pain in the prototype was considered to be insufficient since it only contained the categories “pain” and “cramps”. Both therapists and amputees were used to document respectively describe pain with qualities as well as with temporal or spatial attributes. Since the pain qualities provided by the SF-MPQ became a de facto standard for the characterization of PLP (Crawford, 2009), we assessed the amputees with the SF-MPQ to get an impression of their use. The results show a mean quantity of 4.8 (SD 2.8) pain qualities that were reported per amputee, and it is reasonable to include these pain qualities into CALA. More so, the German Neurological Society recommends to also describe the duration and temporal aspects of pain in addition to the quality (Schlereth, 2020). Concerning the quantification of the phantom limb, it was suggested by therapists to use the neutral-zero-position (Ryf and Weymann, 1995) as a baseline for the posture. The quantification of the shape could be expressed as a percentage of change compared

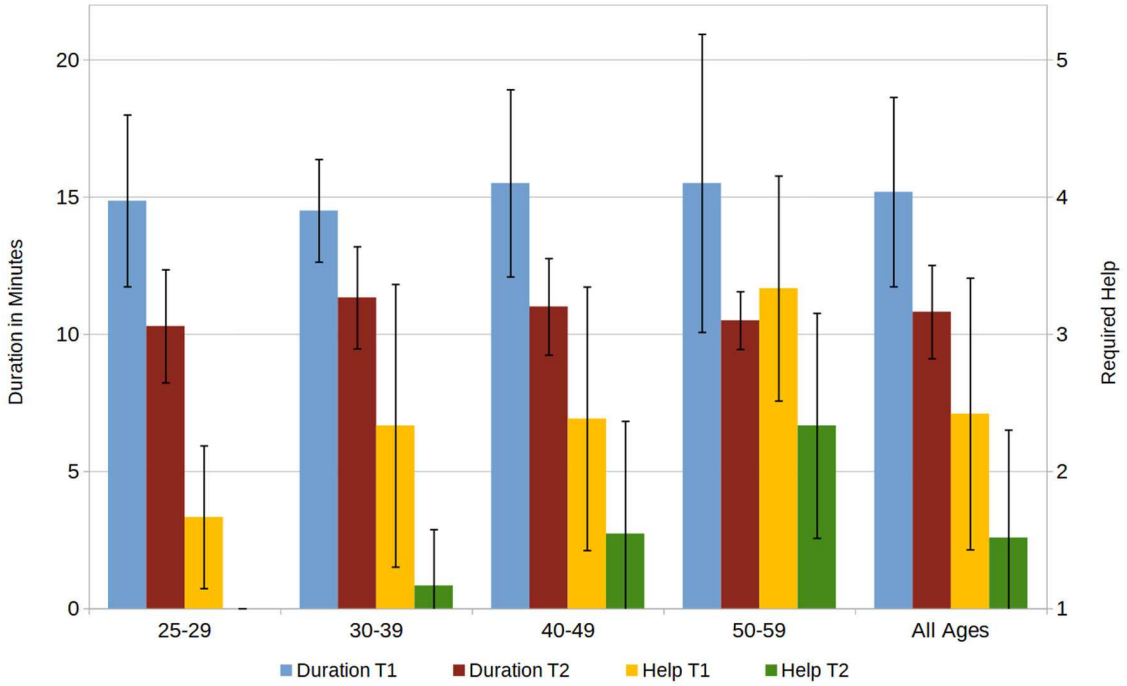

Figure 3.4: The required duration in minutes for the first and second documentation task (T1, T2) of the prototype evaluation with therapists and the required assistance, rated on a 1-5 Likert scale (1="no help", 5="a lot of help"). The error bars represent the SD. From Bressler *et al.* (2022), Frontiers in Rehabilitation Sciences, CC BY 4.0.

to the unmodified original. Since pain is drawn on the surface of the avatar with a specific intensity, each intensity can be expressed by its covered area.

3.1.4 Usability of the Prototype

The usability of the prototype was rated by therapists with the SUS and resulted in a mean score of 81.7% (SD 11.2), which represents good usability. The diagnostic and therapeutic values of CALA were rated on a 1-5 Likert scale (1="very low", 5="very high") with mean values of 4.2 (SD .8) and 4.15 (SD .1). The mean duration required by therapists to complete a documentation task decreased from 15.2 (SD 3.5) minutes for the first task to 10.8 (SD 1.7) minutes for the second and did not differ much across age groups. The required assistance, measured on a 1-5 Likert Scale (1="no help", 5="a lot of help"), decreased from an average of 2.41 (SD .99) to 1.51 (SD .78). In both runs, the value was the lowest for the youngest age group and increased with the age of the groups (see Fig. 3.4). In the semi-structured interviews, we asked the therapists how to facilitate the use of CALA, and most frequently mentioned were bigger controls and text of the interface (9 mentions) and

a reduced interface by pre-selecting the diagnosis (7). User observation revealed the occurrence of operational errors, such as manipulating the wrong side of the body, or difficulties regarding the user interface, e.g., when rotating and moving around the 3D avatar. In particular, the task of positioning specific body parts to adjust them or draw on them was time consuming, tendentially more so for the older participants. Another slowdown was the change between the application interfaces of MakeHuman and Blender, which resulted in differently looking environments that required different handling of the 3D avatar.

The use of CALA in clinical practice requires a fast documentation process that needs to be done together with the patient within a regular therapy session of approx. 50 minutes. This renders the duration of 10 minutes, as it was measured for the second task, still remarkably high. The biggest hurdles for continuous user flow can be identified as the size of the control elements, which could become scalable in a future version to ensure optimal adjustment for all display sizes, and the lack of a streamlined and uniform user interface. Furthermore, accidental adjustment or drawing on the wrong side of the body could be prevented by a pre-selection of the affected limb and the amputation level, which could subsequently limit the editable area of the avatar to the selected limb and reduce the options of the user interface. The preparation for drawing on certain parts of the avatar without them being occluded could be facilitated by automatically focusing on a specific body part, instead of manually rotating and zooming in on the avatar. A further complication occurred when drawing pain in places that were hard to reach, e.g., the palm of a closed hand. Such could be avoided by an option to switch on and off the visualization of the specified posture and shape.

3.1.5 Limitations

The sample size of only 33 therapists is rather small, even more so because all participants were recruited from only 5 different facilities. It can be assumed that the inclusion of more facilities would have brought more diversity to the results, concerning the documentation methods as well as the additional requirements. The evaluation of the functional range with 22 amputees also represents only a part of the various manifestations of PLS and PLP.

3.2 Development of the full Application

The positive feedback during the evaluations and the repeatedly expressed demand for such a tool led to the development of a full version of CALA[3]. Since the collected

[3] `https://www.playbionic.org/cala` (Access: 10th of July 2025)

requirements made it impossible to develop the prototype any further, the full version had to be developed from scratch. The use of the game engine Unity[4] enabled us to target multiple platforms such as Windows, macOS and Linux and mobile devices such as Android tablets. While the development is still ongoing, CALA is already being used successfully in practice. In the following, a brief overview of the main functionality of CALA will be presented to highlight the most important learnings from the study. CALA is a desktop application, and files are saved locally. To speed up the documentation process, a base model has to be created initially for each patient. In the base model, the avatar can be adjusted in terms of gender; optionally, the skin tone can be adjusted in the settings but is not linked to a specific patient file, and further customization of the avatar itself is not possible. Amputations are also specified in the base model by choosing from pre-defined amputation levels (see Fig. 3.5). The hereby determined separation between phantom and residual limb is visually reflected and serves as border to clearly assign painted sensations to either the phantom or the residual limb. If no amputation is specified, the respective limb can be adjusted and painted on as a whole, e.g., for the documentation of neuropathic pain.

The interface of CALA is uniform and all modifiers to adjust the avatar can be controlled with value sliders. The process of focusing the view on specific body parts in order to paint them was automated and can be achieved by double-clicking on the respective part of the avatar. The neutral-zero position (Ryf and Weymann, 1995) is used as baseline for the posture and the deviation of individual joints is used for quantification (see Fig. 3.5). The sensation in fingers and toes can be captured with more detail by adjusting the position and shape individually for all phalanges of the fingers and for all toes. The pain documentation was extended to capture not only “pain” and “cramps”, but “sensations” in general. These sensations are drawn directly on the avatar with a specific intensity, ranging on a 0-10 numeric rating scale (NRS), and can be attributed by pain qualities taken from the SF-MPQ. Multiple layers can be used to draw different sensations and later quantify them separately. In addition to pain, the perceived “awareness” or “presence” of the phantom limb can also be drawn on the avatar and is illustrated by different shades of transparency (see Fig. 3.3). Currently, CALA is extended with customizable extra fields to facilitate the integration of questionnaires or custom surveys. This enables CALA to be quickly set up for specific studies or other application domains, e.g., CRPS or paraplegia.

[4] Consecutively using the versions 2020.3.36f1, 2021.3.11f and 2022.23f1

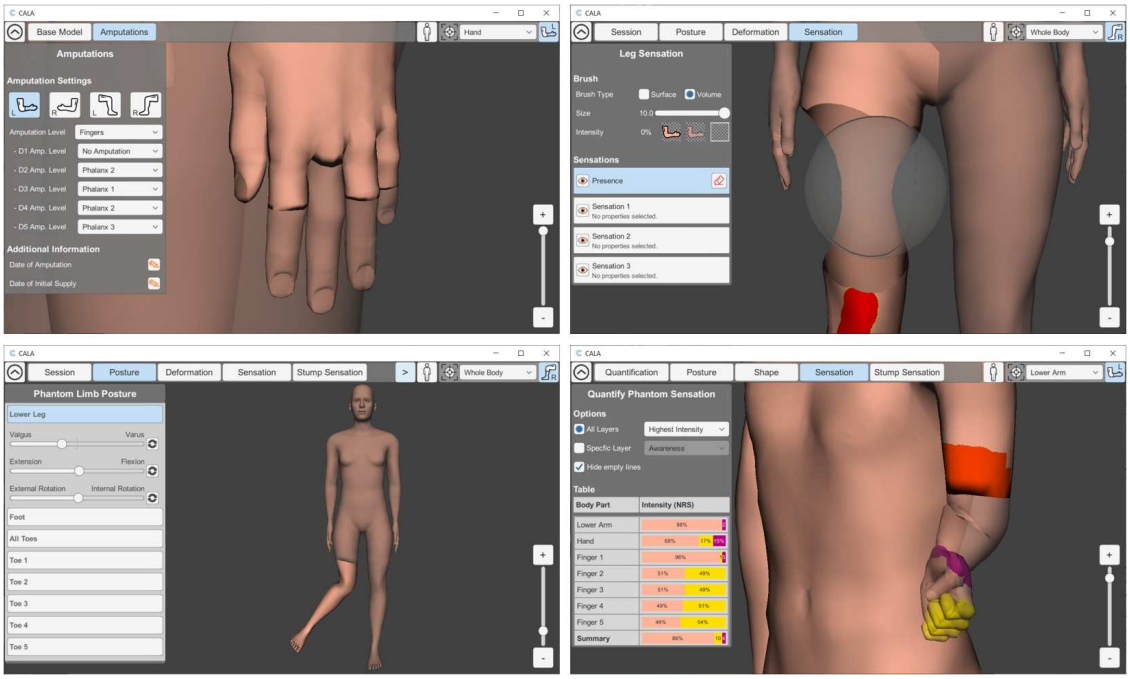

Figure 3.5: The full version of CALA (version 0.94.2, accessed in June 2025): **(A)** amputation levels can be defined in the base model; **(B)** The presence of the phantom limb and pain intensities can be drawn directly on the avatar; **(C)** the position of the limb is adjusted with the neutral-zero-position as baseline; **(D)** the quantification of pain intensities drawn on the phantom limb and the residual limb are expressed as the percentage of covered surface area.

3.3 Outlook

The development of CALA is still ongoing, and its functionality will be further extended, e.g., to enable the phantom being positioned beyond the residual limb, to capture movements of the phantom or by an "undo" function. CALA should be further validated as a pain questionnaire and therefore could incorporate metrics of already validated questionnaires, such as the Pain Rating Index provided by the SF-MPQ. However, it might be necessary to develop and validate new metrics that consider all dimensions of the CALA limb.

Furthermore, it is conceivable to use CALA in therapy, in particular for forms that are based on mirror therapy or motor imagery (Herrador Colmenero *et al.*, 2018). These approaches are not limited to the treatment of PLP but could further be used e.g., in stroke or CRPS patients. Finally, with CALA we have developed a highly automated process to generate virtual representations of phantom limbs. This, in combination with VR, offers completely new ways for patients to experience and engage with their phantom limb, and would be an interesting starting point for research, e.g., to better understand mirror therapy and to make it more efficient (Rothgangel and Bekrater-Bodmann, 2019).

Chapter 4

StableHandVR

StableHandVR is a serious game that supports players in regaining the mobility of their hands and fingers after a traumatic injury. The game aims to transfer hand and finger exercises into an engaging virtual environment by making use of the Meta Quest 2, a standalone and fully immersive VR HMD with integrated optical hand tracking. In a previous study, the principal feasibility of such a VR game was already tested with able-bodied participants (Pereira *et al.*, 2020). However, the presented game design did not consider patients with an impaired hand function and lacked a concept for engagement. This resulted in 2 key requirements for the development of a new prototype: First, the game should be capable of recognizing the execution of exercises, even if performed only partially. Second, the game should provide various motivational elements to engage a wide spectrum of player types over a period of 2-3 weeks. The game principle of StableHandVR features multiple training stations within a farm-themed environment. Each training station is thematically linked to a specific task (e.g., milking cows), which becomes fulfilled step by step as the exercises are repeated. Each repetition is tracked by the game, which calculates individual range of motion (ROM) boundaries for each player to determine when a movement repetition is considered as completed (see Fig. 4.1).

Methods The game was developed and evaluated in 3 phases: First, a prototype was implemented to evaluate the basic game mechanics. Three training stations were embedded in a farm setting and 6 exercise movements had to be performed at each station. A dog accompanied and guided the player, and 4 motivational game elements were conceived: *Storytelling*, *Unlocking Rewards*, *Traffic Light Hands*, and *Scoring*. The prototype was evaluated with 18 able-bodied participants and 7 inpatients, who had to complete 4 VR sessions with a maximum duration of 15 minutes each. During the sessions, the participants were observed and assisted by the investigators. After each session, participants had to rate their experience using the Intrinsic Motivation Inventory (IMI) questionnaire (Reynolds, 2007) and their feedback on the game was collected using semi-structured interviews. Based on this feedback, version 1 was developed, which provided a fully explorable farm

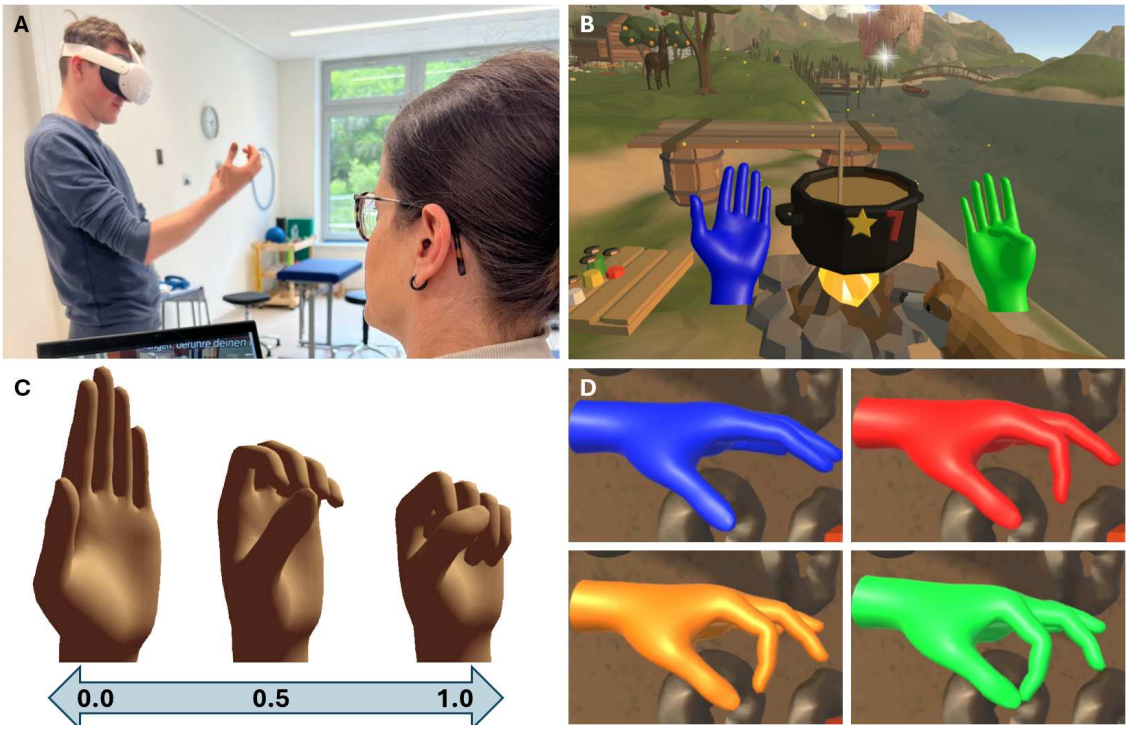

Figure 4.1: **(A)** A participant, equipped with the Meta Quest 2, plays StableHandVR. **(B)** During the exercises, a counter displays the remaining repetitions. **(C)** To track the execution of exercises, each exercise movement was defined as an interval spanned by 3 positions. **(D)** The motivational element Traffic Light Hands encouraged the players to push their movement limits by providing direct feedback through changing hand colors. B, C and D from Bressler *et al.* (2024), JMIR Serious Games, CC BY 4.0.

and a pool of 17 exercise movements. For the evaluation, 20 inpatients were divided into an intervention and a control group and had to complete 12 VR sessions on consecutive weekdays with a maximum duration of 30 minutes each. In each session, the participants in the intervention group played StableHandVR and received 2 mandatory tasks to complete a specific training station. Over the course of the game, more stations got unlocked and could be played as additional tasks after completing the 2 mandatory stations. Meanwhile, the control group watched stereoscopic 360° videos, also with the Meta Quest 2 HMD. All participants were observed and assisted by the investigators during the sessions and subsequently queried with 4 IMI subscales (*interest and enjoyment*, *effort*, *pressure*, and *usefulness*). Participants of the intervention group were additionally queried with the Mobile Application Rating Scale (MARS) questionnaire (Terhorst *et al.*, 2020) and interviewed. During the sessions, the game also automatically recorded usage data for further analysis. Subsequently, version 2 was developed, which differed primarily in a more accurate tracking of exercise movements and a revised interaction

design. The evaluation of version 2 was performed similarly to version 1, with an extended task for the control group and the SUS questionnaire as addition for the intervention group (see Fig. 4.2).

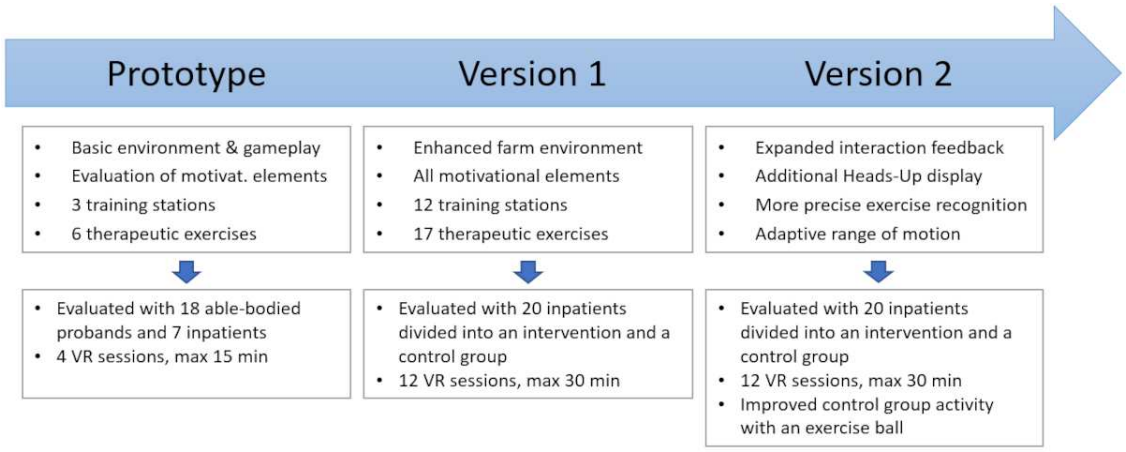

Figure 4.2: The 3 stages of the iterative development process of StableHandVR (from Bressler *et al.* (2024), JMIR Serious Games, CC BY 4.0).

4.1 Results and Discussion

The iterative design approach proved to be successful and helped to identify and overcome several usability issues, especially regarding the clarity of the interaction design and the recognition of exercise movements. In addition, lots of suggestions and requests regarding the overall design and additional playable content could be collected from the patients, but also from the therapists involved in the study, and were subsequently included in the development process.

4.1.1 Acceptance

StableHandVR was often referred to as a holiday on the farm. Participants liked the idea of a game that would support them in exercising and the setting of a farm and nature, a design decision inspired by literature (Ulrich, 1984). Amongst all 65 participants from all 3 evaluations, no motion sickness or discomfort were reported during the VR sessions, only one patient answered with “don’t know”. The overall response to the VR experience was already positive during the prototype evaluation and during the evaluation of version 1 and 2, inpatients from both the intervention and the control group reported that they enjoyed the VR sessions and perceived them as vacation from their inpatient stay. They described that they felt being transported to another place and experienced a sense of tranquility. The

immersive environment made them lose track of time and the virtual representation of their hands made them forget about the injury. This impressively confirms the power of VR and its potential as therapeutic tool (Bui *et al.*, 2021; Hoffman *et al.*, 2020; Sanchez-Vives and Slater, 2005). Concerning the game experience of the intervention group, the overall concept and setting were perceived as pleasant and appealing, and the virtual hands and the interactive aspect of the exercise stations impressed the patients. The companion dog was perceived as adorable and participants used to pet it; despite this interaction neither being intended nor supported through any feedback from the game.

4.1.2 Motivational Aspects

Four game elements were developed with the goal of stimulating both the intrinsic and extrinsic motivation for a spectrum of different player types, e.g., the *achiever* or the *explorer* (Tondello *et al.*, 2016). During the evaluation of the prototype, all 4 motivational elements received high IMI scores which showed no significant differences across the 4 elements or over the course of the 4 sessions. While the IMI scores did not vary much between the elements, the semi-structured interviews, however, revealed clear differences in popularity. The *Scoring* element was considered meaningless already in the prototype, since most participants would always score the maximum number of points. It was however stated that an improved *Scoring* element would be appreciated. When it was removed in version 1, patients repeatedly expressed their demand for any kind of meter that would enable them to observe progress. In version 2, an improved variant of *Scoring* was re-introduced but experienced the same difficulties as in the prototype, since most patients immediately reached the maximum ROM for most of the exercises. For such an element to work, it has to be meaningful to the player (Cugelman, 2013) and therefore another metric must be used, e.g., the progress of days. While all elements except for *Scoring* were favored by the patients in the prototype, in version 1 the element *Traffic Light Hands* was outstanding amongst the others. It was highlighted as motivating to push one's personal ROM boundary and also served as guidance for a correct execution of the exercises. Regarding the 2 remaining motivational elements, *Storytelling* was developed in version 1 to populate the farm with non-playable character (NPC) that provided the player with daily tasks. *Unlocking Rewards* ensured the progressive activation of further training stations, which provided variety and helped to prevent the patients from getting bored by playing the same stations over and over again.

To measure the impact on motivation, participants from both the intervention group and the control group were queried with the IMI, and the number of completed training stations per day was measured. In Version 1, all 4 IMI subscales were higher for the intervention group than for the control group and significant differences

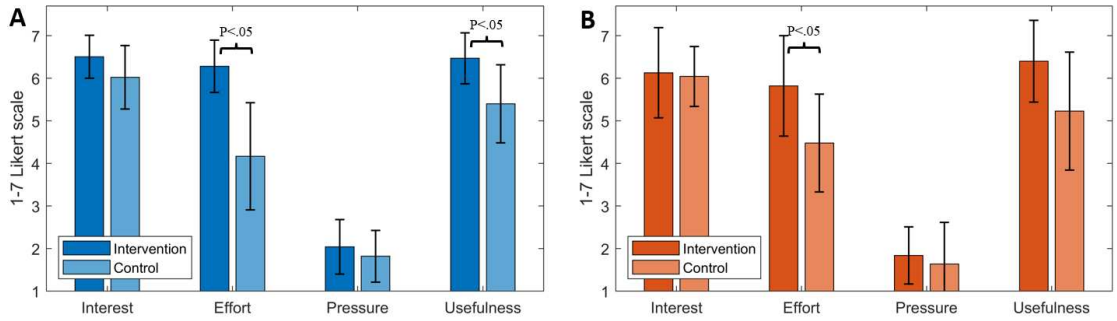

Figure 4.3: The mean scores and SD of the Intrinsic Motivation Inventory (IMI) subscales of the intervention group compared to the control group for **(A)** version 1 and **(B)** version 2 show significant differences in 2 respectively 1 scale (from Bressler *et al.* (2024), JMIR Serious Games, CC BY 4.0).

were found for 2 subscales: *effort* (P<.001) and *usefulness* (P=.02) (see Fig. 4.3). The MARS questionnaire resulted in high mean scores for all 4 subscales with no significant differences between them. In version 2, the scores of the IMI subscales were again higher for the intervention group with one significant difference in the subscale *effort* (P=.02). The mean MARS scores only differed slightly compared to version 1 and the SUS rating resulted in a mean score of 86.9 (SD 3.3) which represents excellent usability. The mean number of training stations that were completed by the intervention group was always higher than the required daily minimum except for day one and day 10 in version 1 and for day one in version 2 (see Fig. 4.4). The comparison between version 1 and version 2 shows a significant increase (P=.008) of stations played per day. While the game can be considered effective to increase the motivation of its players, not all of them were engaged to the same extent and it was observable that the engagement also faded at different rates. This emphasizes the difficulty of addressing a broad spectrum of player types and shows that StableHandVR would still benefit from a greater variety in incentives for the players (Tondello *et al.*, 2016). Measured by the number of completed stations per day, motivation was significantly increased from version 1 to version 2, while the mean IMI scores for both versions were similar. It can therefore be concluded that the usability issues mainly affected extrinsic motivation while they did not harm intrinsic motivation.

4.1.3 Usability

Although using Meta Quest 2 was unfamiliar for most participants at the beginning, they showed little fear of contact in operating the HMD and some of the patients were even eager to operate the device fully by themselves. Most patients were able to play version 1 of the game independently after 2 initial days, except

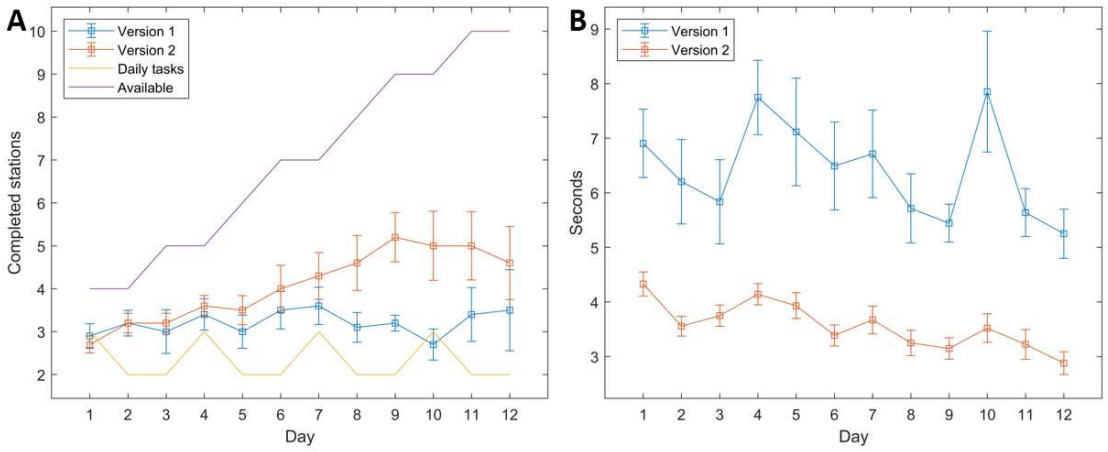

Figure 4.4: **(A)** The mean number and SE of completed stations in version 1 and 2, as well as their required minimum and maximum specified by the daily tasks and the number of available stations for each day. **(B)** The mean duration and SE required for the repetition of one repetition of one exercise movement in version 1 and version 2. New exercises were introduced on days 1, 4, 7, and 10. From Bressler *et al.* (2024), JMIR Serious Games, CC BY 4.0.

for the introduction of new exercises, which required help from the assisting physiotherapist. Some individuals, however, remained dependent on assistance during the whole course of the interventions, due to difficulties with orienting on the farm, or because it was not clear for them where to focus their gaze on when performing the duty at the respective station (e.g., milking the cows, feeding the sheep). Also, some stations contained visual but no audible feedback to indicate successful exercising. All of this made it unclear when a single repetition was completed, and several participants wished for a counter to display the number of remaining repetitions. These insufficiencies were addressed in version 2. A navigation arrow helped the player to keep the orientation by always pointing towards the current task or action. Exercising was facilitated by adding a counter to keep track of the remaining repetitions and audiovisual feedback was consistently provided at all training stations to clearly indicate the successful completion of the exercise repetition. These improvements enabled most patients to play the game without assistance, except for the introduction of new exercises.

For the prototype, we developed a component, which could track the repetition of exercise movements, even if they were not fully executed, e.g., due to an impaired hand function. For the 6 movements of the prototype, the component worked observably well but was experienced as unsatisfying by several participants. The biggest challenge for the participants was to keep their hands in a position where they could be fully captured by the cameras in the HMD. Artificial light and result-

ing shadows were identified as additional disruptive factors. After the introduction of all 17 exercises in version 1, due to their limited hand function some patients were not able to perform all of them in a way that the game could recognize them. In version 2, the exercise tracking could be improved by defining a middle position for each exercise (see Fig. 4.1.C). This enabled a more accurate estimation of the current hand position in the movement interval of the exercise and caused the patients observably less difficulties than in version 1. The improvement is reflected by the significant reduction of the mean duration ($P<.001$) required for a single exercise repetition from version 1 to version 2 (see Fig. 4.4). To further improve this component, we suggest the implementation of joint weights to define the importance of individual joints for each exercise. As a result, exercise tracking would become more robust, which would make the exercises more accessible.

4.1.4 Limitations

Despite the significant differences in motivation between the investigation and the control group, the actual effectiveness of the game to keep up motivation can be questioned. It must be considered that the study was conducted in a supervised setting, which is known to create better results than unsupervised exercising (Minetama *et al.*, 2019). In addition, the patients were in an unfamiliar environment and could not continue their daily routines, which could also have increased their willingness to exercise. Another limiting factor was the small sample size and the short evaluation period of only 12 days. For the evaluation of long-term engagement, an often used evaluation time span is 3 months (Kayali *et al.*, 2018). This was not possible for the conducted study due to the much shorter availability of the patients of only 3 weeks.

4.2 Outlook

As a next step, StableHandVR should be evaluated at the patient's home, following the inpatient stay. This use case might generate the biggest benefit, as continued consistent exercising of the hand within an unsupervised setting would have a very positive effect on the further healing process (Minetama *et al.*, 2019). Such a study would furthermore allow for a longer intervention period and more meaningful results, if no other therapy were conducted at the same time.

Further Gamification To keep up the players' engagement for a period longer than 12 consecutive weekdays, the motivational elements need to be expanded and improved, in particular the *Scoring* element. A lot of ideas have been collected and

conceived during the development and evaluation process and there was no time to implement all of them. Instead, a brief overview is given here:

It was evident that several patients desired some kind of meter that could indicate progress. Such an element is desirable in general, since it impacts the intrinsic motivation of the patient (Kayali *et al.*, 2018). By using a more meaningful value than the ROM of the player, e.g., the number of completed days, the story would become more coherent and might satisfy the underlying mechanism of this element (Caserman *et al.*, 2020). The introduction of badges could help to set incentives for certain meaningful goals (e.g., consistent daily exercises, fulfilling all extra tasks) and mini games could tie the player more closely to the game (e.g., fishing in the lake, or even finger-targeting tasks such as playing a virtual piano or stone-scissor-paper against NPCs). A leaderboard would make badges and other rewards comparable to the achievements of other patients. Customizing the virtual hands (e.g., adding a wristwatch or special effects like encircling sparks) could foster intrinsic motivation (Birk *et al.*, 2016) and customizing the farm (e.g., custom color of the farm house, the placement of additional objects) could help to create a more personalized experience, which is important for long-term engagement (Kayali *et al.*, 2018).

Telerehabilitation A current hurdle for the completely autonomous use of StableHandVR is the introduction of new exercise movements, which currently still needs to be supervised by a physiotherapist. This is mainly due to the lack of wrist and arm tracking, which causes the game to not be fully able to monitor all limbs of the patient. An option to make StableHandVR remotely usable could be the inclusion of video conferences with a therapist to teach new movements and regularly check on the patient. Such a supervised environment might also have a beneficial impact on motivation due to the big-brother effect (Minetama *et al.*, 2019) and could support the social component of the game, which serves as motivation itself (Krath *et al.*, 2021).

Chapter 5

PhantomAR

Despite its name, PhantomAR is an **M**R system, that was designed to extend traditional mirror therapy beyond its restriction to seated and unilateral movements. PhantomAR targets patients with a transradial amputation and enables them to use a virtual hand that is augmented on the stump of their residual limb in a virtually enriched environment. PhantomAR makes use of the Microsoft HoloLens 2, a holographic MR HMD that overlays the real world with virtual objects. The spatial mapping of the HoloLens 2 recognizes elements such as the floor, walls, or tables, and PhantomAR uses them to dynamically generate virtual environments that incorporate the current surroundings of the player. Patients can use both the virtual and their real hand to interact with virtual objects, e.g., pushing them off a table or grabbing and manipulating them with both hands. Since stress, frustration or discomfort are factors that could affect PLP adversely, the gameplay of PhantomAR is solely curiosity driven. Patients can freely explore 7 interactive environments without the possibility of failure or underperforming due to no goals, competition, or pressure.

Methods The evaluation of PhantomAR was conducted with 18 participants, including 10 healthy individuals and 8 patients with unilateral transradial amputations who had moderate to high PLP. Out of the 8 patients, 5 already used a prosthesis, however none of them did so regularly. For the intervention, participants had to play 4 different scenarios for a total of 30 minutes, which was repeated after a 10-minute break. During the MR sessions, participants were observed and received assistance if required. Before, during and after the whole intervention, patients rated their PLP using a 0-10 NRS and the skin temperature of their residual and intact limb were measured with a contactless infrared thermometer. PLP was also assessed before and after the intervention with the SF-MPQ. After the intervention, the usability of PhantomAR was assessed by all participants with the SUS questionnaire, the Game Experience Questionnaire (GEQ) (Ijsselsteijn *et al.*, 2013) and a self-developed survey. Finally, the embodiment of the virtual arm was compared to a non-anthropomorphic representation of the hand, a purple tentacle, by

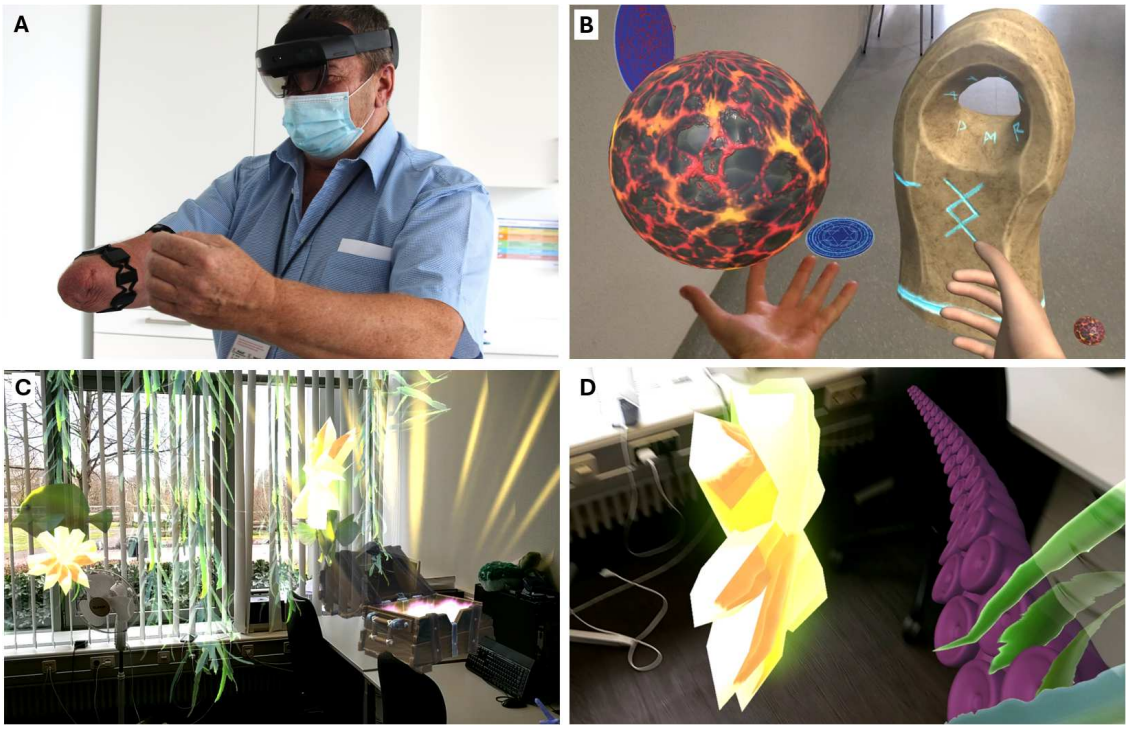

Figure 5.1: **(A)** A patient plays PhantomAR, equipped with a Microsoft HoloLens 2, a Thalmic Labs Myo Armband around his stump and another one around his upper arm. **(B)** Virtual objects could be manipulated with the real and the virtual hand (from Prahm *et al.* (2025), Journal of Neuroengineering and Rehabilitation, CC BY 4.0). **(C)** All environments were dynamically generated based on the real surroundings, using walls, the floor and desks. **(D)** A tentacle was used to evaluate the effects of using a non-antropomorphic representation of the phantom limb in comparison to a human hand.

assessing both with the Prosthesis Embodiment Scale (PES) (Bekrater-Bodmann *et al.*, 2023).

5.1 Results and Discussion

The aim of PhantomAR was to develop a mobile therapy tool for the alleviation of PLP. Based on the operating principle of mirror therapy, PhantomAR should enable the user to move around freely and to interact with virtual objects bi-manually, thus overcoming the limits of traditional mirror therapy.

5.1.1 Alleviation of Phantom Limb Pain

All patients reported a reduction of PLP; however, we observed high variability in how patients experienced PLP during the intervention (see Fig. 5.2). Overall, PLP was significantly reduced by 58% on the NRS ($P<.001$) and 45% on the SF-MPQ Pain Rating Index ($P<.001$), which can be considered as clinically meaningful (Tilak *et al.*, 2016). Thus, PhantomAR shows promising results for a proof-of-concept study. Due to the small sample size and the single-session design, it was not possible to capture the long-term impact on PLP. A long-term study would also be required to gather more insight into the potential influence of distraction and cognitive load through immersive tasks on the reduction of pain and the sense of embodiment.

Skin temperature measured in both the healthy arm and the residual limb increased in all conditions from pre to post intervention. The residual limb was on average 3 °C colder than the unaffected arm and increased by a mean value of 1 °C after intervention. A correlation analysis between the intensity of PLP and the temperature indicated no significant linear relationship. While higher skin temperature is reported to be an indicator for PLP (Angrilli and Köster, 2000), the temperature increase between pre and post evaluation is most likely caused by an increased blood flow and widened blood vessels, or by shifts in the sense of ownership and embodiment (Rohde *et al.*, 2013). While no significant correlation between PLP and skin temperature was found, patients with higher PLP prior to the intervention tendentially also had a higher skin temperature in their residual limb.

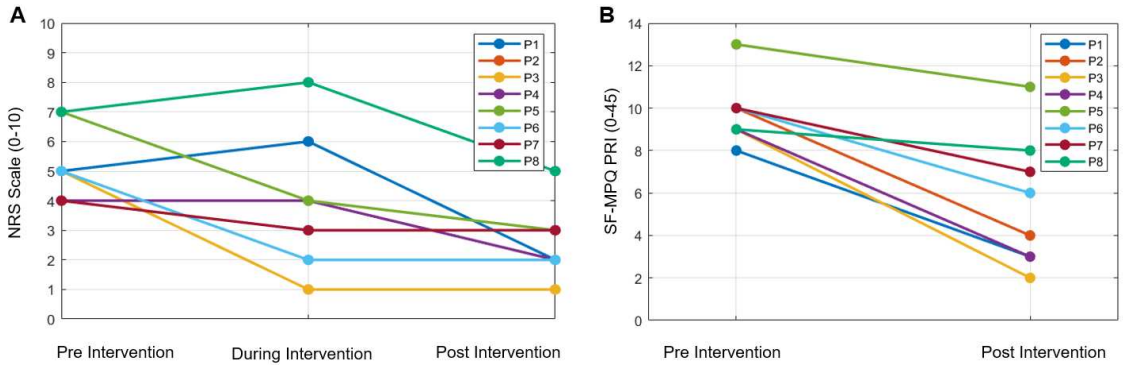

Figure 5.2: The progression of PLP was significantly reduced ($P<.001$) from pre to post intervention when assessed with both **(A)** the Numeric Rating Scale and **(B)** the Short Form McGill Questionnaire Pain Rating Index. Both are own illustrations based on the data from Prahm *et al.* (2025).

5.1.2 Embodiment

The augmented virtual hand created strong senses of ownership and agency, which is represented by high PES scores and also reflected by the successful alleviation of PLP. The sense of *ownership* was slightly higher for the amputees while the *anatomic plausibility* was higher for the able-bodied participants. However, none of the differences were significant. Some amputees, who had not used their prosthesis for a long time, reported that they felt their phantom hand once again and they felt it grow into the virtual hand. During the interventions, participants referred to the augmented hand as "my hand". The exploration of a non-anthropomorphic representations of the virtual limb was inspired by real-world prosthesis usage, where the prosthesis does not necessarily have to resemble a hand and is rather understood as tool. For both the able-bodied participants and the amputees, the non-anthropomorphic tentacle resulted in a lower median PES score for *ownership*, a higher *sense of agency* and a lower *anatomical plausibility* compared to the realistic hand model. No differences between the 2 groups were significant. The self-developed survey revealed that while the amputees embraced the idea of using a different representation, they still preferred an anthropomorphic representation of their missing limb. These results are confirmed by literature, where the sense of ownership is reported to be higher for a realistic hand model (Lin and Jörg, 2016), and the sense of agency is higher for non-anthropomorphic representations, since the abstract representations of tasks, e.g., opening or closing the hand, have little reference to reality and therefore result in a better illusion than a realistic hand (Argelaguet *et al.*, 2016). The use of vibro-tactile feedback induced at the residual limb was reported to greatly enhance the immersive experience of grasping objects and might have a positive effect on the sense of embodiment, PLP and distortions in the phantom limb (Risso *et al.*, 2022). Therefore, its use should be given greater consideration for future versions of PhantomAR.

5.1.3 Acceptability and Usability

PhantomAR was positively received by the participants and received a mean SUS score of 89.6% from the amputees and 90.8% from the healthy participants, both representing excellent usability. Wearing the HoloLens 2 was not described as uncomfortable, and no participant reported the occurrence of motion sickness. The limited field of vision of the holographic display initially felt restricted to most participants, but they reported that they forgot about it once being immersed in the application. The MR experience and especially the interactions with virtual elements were described as novel, interesting and challenging. For both groups, the GEQ resulted in high scores for the 3 subscales *positive affect*, *immersion*, and *flow*, and low scores for the 2 subscales *negative affect* and *challenge*. However, it was obvious that some participants needed more clues and instructions to play

PhantomAR autonomously. While some participants were able to explore the scenarios independently, others needed a lot of assistance, especially at the beginning, and it was necessary to guide them towards and through less obviously designed game components. Also, the concept of generating motivation by curiosity was not suitable for all participants, and greater consideration of different player needs (Tondello *et al.*, 2016) might be reasonable to increase the efficiency of PhantomAR. The low score of the GEQ subscale *challenge* confirms this observation and we suggest to add challenging mini games to comfort a wider spectrum of player types (Zagal *et al.*, 2013).

The bi-manual interaction with virtual objects worked sufficiently well to immerse the participants in the game and for some even well enough to enter a flow state, which is known to heavily impact the intrinsic motivation (Krath *et al.*, 2021). However, this was not equally achievable for all patients. Based on our observations, the main complication here was the control of the virtual arm, which apparently is a typical issue for self-developed input systems used in serious games for upper limb rehabilitation (Koutsiana *et al.*, 2020). In fact, tracking the residual limb to control the virtual arm caused several difficulties that limited the overall usability of the system. The first challenge concerned the setup, in particular the process of properly establishing Bluetooth connections to all IMU and EMG sensors and subsequently attaching them to the participant. In the worst case, this process could take up to 10 minutes, which we consider to be a problem for the use in a clinical or therapeutic setting. The second challenge was tracking accuracy, which was only sufficient after switching from using the included IMU sensor of the EMG bracelets (Thalmic Labs Myo Armbands[1]) to dedicated IMU sensors (MbientLab MetaMotionRL[2]) due to a strong horizontal drift of the bracelets. However, despite the reduction of drift it was still necessary to recalibrate the position of the virtual arm every few minutes. Virtual limb control was further complicated due to the lack of a separately measured shoulder rotation, which instead moved along with the HMD. This made it difficult for patients, e.g., to look at their upper virtual arm. Finally, limb control was complicated due to the limited field of vision of the holographic display, which required them to focus their gaze on the virtual limb in order to make it fully visible.

Overall, the immersive MR experience proved to be sufficient to induce agency and ownership, and the spatial mapping of the HoloLens 2 impressively demonstrated the potential of fusioning virtual scenarios and objects with the real world, which is suggested to play a major role in future medical application (Brassel *et al.*, 2021). However, such advanced spatial mapping is no requirement for the main purpose of

[1]The product is no longer available. Open-source projects and specifications for the Myo Armband can be found at `https://github.com/thalmiclabs` (Access: 10$^{\text{th}}$ of July 2025)

[2]`https://mbientlab.com/store/metamotionrl/` (Access: 10$^{\text{th}}$ of July 2025)

PhantomAR, and the cumbersome handling of HoloLens 2, in particular the limited range and contrast of the holographic display, make it reasonable to abandon this device in favor of a more user-friendly solution.

5.1.4 Limitations

This study was designed as a feasibility study and the findings regarding the efficacy of PhantomAR are based on 8 amputees. For any comparisons to traditional mirror therapy or other digital solutions, a longitudinal controlled study would be necessary. To observe long-term effects on PLP, the period in which the interventions take place, and the observation period would have to be extended. Finally, the restricted field of vision of the HoloLens 2 and the insufficient tracking solution for the residual limb might have limited the degree of immersion and thus the efficacy of PhantomAR.

5.2 Outlook

For further development, we think that abandoning the HoloLens 2 in favor of another HMD would be an essential step towards an improved user experience, and a suitable replacement candidate is the Meta Quest 3. Although the spatial awareness of this device is heavily limited in comparison to the HoloLens 2, its pass-through display provides a much wider range of vision and a better, because opaque, blending of virtual objects with the real world. The user experience could further be improved by adding an additional IMU sensor to measure the shoulder rotation and the periodically required re-calibration of the virtual arm could be facilitated by incorporating this process into the gameplay. While PhantomAR is currently only suitable for amputees with a trans-radial amputation[3], it could easily be extended to cover patients with trans-humeral amputations[4] by using a fixed or controllable elbow joint. Since the majority of amputations concern the lower limb (Sparling *et al.*, 2024), it seems reasonable to include this target group as well. However, this would require a completely new concept for interactions, e.g., seated activities that incorporate the use of a pedal crank (Ambron *et al.*, 2021). Since the virtual hand is controlled like a myoelectric prosthesis, PhantomAR could be further developed towards a serious game for the training of myoelectric prosthesis control (Kristoffersen *et al.*, 2020). Many patients abandon their prostheses due to pain or discomfort, e.g., caused by a not perfectly fitting prosthesis shaft (Aranda-Moreno *et al.*, 2019), and PhantomAR could serve as training tool for the time span after the amputation and before a shaft can be properly fitted. The preview on

[3] With a remaining forearm stump

[4] With a remaining stump of the upper arm

the alleviation of PLP through the use of a prosthesis (Flor, 2002; Kaur and Guan, 2018) could be a crucial incentive towards the active use of their future prosthesis.

Chapter 6

General Discussion

The aim of this dissertation was to conceive and develop digital tools that support patients, in particular amputees and patients with impaired hand function, in their rehabilitation process. This process included the investigation and elaboration of requirements and their subsequent implementation and evaluation.

6.1 User-Centered Development

For the development of all 3 applications, the Unity game engine[1] was used and clearly demonstrated how much the process of creating real-time 3D applications for multiple platforms and devices has been facilitated in 2025. This tremendously lowers the barriers for prototypes and it can be assumed that the research trend towards more tailor-made serious games and targeting more specific health issues will be further amplified (Kato, 2010; Kayali *et al.*, 2018). However, it should also be mentioned that the technical development can quickly become challenging again once the beaten track is left. We experienced this in particular while developing the limb tracking component of PhantomAR.

Although the technical development has been strongly facilitated, it still remains a challenge to design a tailor-made application that satisfies the needs of all stakeholders and across all use cases. It was therefore important to involve patients and therapists and work towards a mutual understanding of all needs. We followed the recommendations for a user-centered design for the development of all 3 applications, which are: a multidisciplinary team, the active involvement of all users, a clear understanding of the requirements, and an iterative design process (Maguire, 2001). While the user-centered approach was part of the methodology for StableHandVR, the prototype and the full version of CALA as well as of PhantomAR also included design and evaluation loops in their development process. Most of the requirements were collected through the "official" methodology, in particular

[1] The versions 2019.4.20f1, 2020.3.11f1, 2020.3.36f1, 2021.3.11f1 and 2022.23f1 were consecutively used.

through the semi-structured interviews, but a part that must not be neglected also came from simply observing the users and from conversations between door and door. For future studies, it might be beneficial to use scientific methods as well to analyze these spontaneous exchanges of information, probably with methods such as grounded theory (Adams *et al.*, 2008) and thematic analysis (Braun and Clarke, 2006). It should be mentioned that the quantitative methods used in the presented studies, such as the SUS, the GEQ and the MARS, proved to be less efficient in gathering useful information regarding usability issues when compared to the semi-structured interviews. Also, the results from the questionnaires were tendentially more well-meaning than the responses in the interviews.

6.2 Acceptance, Accessibility and Applicability

The feedback for all 3 applications was predominantly positive. Most patients, in particular those suffering from PLP, were obviously grateful that someone was working on tools with the purpose of improving their quality of life, and they would probably have been positive towards any potential new cure. However, there was also genuine enthusiasm about the applications, and their core concepts were all appreciated. Both therapists and patients saw CALA bridge a gap by facilitating communication and enable a deeper understanding of the characteristics of the perceived phantom limb. StableHandVR was appreciated due to its assistive nature and the appealing environment and was described by several inpatients as highlight of their daily therapy schedule. PhantomAR could generate excitement in particular through the effect of novelty and the immersive feeling of the augmented limb.

Although all 3 applications were well accepted, we observed major differences in their accessibility, especially due to technological barriers. The full version of CALA proved to be almost barrier-free, in particular when it was used with an Android tablet and controlled via touch interaction. In 2025, most people seem to be familiar with this interaction concept and it is conceivable to increase the accessibility of CALA even more by enabling its use on smartphones (Damaševičius *et al.*, 2023). Handling the Meta Quest 2 was rather unfamiliar in the beginning for most patients, but StableHandVR was easy to learn and we think that it could be made suitable for the use post-therapy at the patient's home as well, which might present the most effective use case for StableHandVR (Minetama *et al.*, 2019). In contrast, PhantomAR had several operational barriers that contributed to a rather challenging user experience and might prevent a casual use of the application (Caserman *et al.*, 2020). Some of the existing barriers would be addressable, especially the setup of the IMUs and the drift of the limb tracking. However, the difficult handling of the HoloLens 2 and the limited field of vision could only be improved by switching to another device.

Concerning the applicability for a clinical or therapeutic setting, time represents a further critical factor next to accessibility. The full version of CALA allowed trained therapists to document a patient within 5 minutes and the use on an Android tablet ensured a flexible and quick setup. Therefore, we consider CALA to be applicable, which is confirmed by the already successful use of the full version as documentation tool in a clinical setting. Due to the easy handling of the Meta Quest 2, it was possible to quickly set up the game and trained therapists could supervise at least 2 patients simultaneously, which is promising considered the general shortage of therapists. We therefore consider StableHandVR to be clinically applicable as well. PhantomAR on the other hand clearly missed these requirements due to its technological barriers. The comparison to StableHandVR also shows the advantages of a professional all-in-one solution in terms of flawless user experience. It is, however, doubtable whether consumer-oriented HMDs will provide sufficiently accurate and modular body tracking systems in the near future, and health applications such as PhantomAR will continue to depend on self-built solutions (Koutsiana *et al.*, 2020).

6.3 Therapeutic Benefit

The complexity of the used technologies renders them fragile and high-maintenance and raises the question of their benefit. Are conventional therapy methods still superior due to their visual and haptic realism and low technical and financial effort (Rothgangel and Bekrater-Bodmann, 2019)? Apart from the fact that technology can increase the accessibility of therapy, it is worth taking a closer look at the strengths and weaknesses of the technologies that were used in the applications presented.

Most serious games which target the rehabilitation of the hand and fingers use the touchscreen of a tablet or smartphone (Koutsiana *et al.*, 2020) and are thereby limited in possibilities to design interaction or exercises. The optical hand tracking of the Meta Quest 2 enabled us to create a dynamic system that can cover a wide range of exercises, and its marker-free aspect makes it further possible to conceive scenarios where any skin contact must be avoided, e.g., with burn patients. On the other hand, such entirely virtual interaction provides no haptic feedback at all and, for instance, limits StableHandVR to only train the hand and finger function. Grip strength training could be implemented by including additional equipment, either with a grip strength trainer or by incorporating the generation of EMG signals into the game (Yang *et al.*, 2017; Zhu *et al.*, 2025). However, when concerning the interaction with objects, the lack of haptic and tactile feedback is a clear disadvantage of using immersive VR/MR technologies compared to conventional physical or occupational therapy. Though, there is one exception that renders this disadvantage less significant, namely amputees, where no real hand to interact with is

available in the first place. But even in this scenario, tactile feedback should not be neglected, since multisensory stimulation proved to be useful in PhantomAR and is also known to increase the immersion and further alleviate PLP (Risso *et al.*, 2022).

The greatest strength of interactive digital media applications and immersive technologies in particular is the play of the visual sense. The ability to visualize any custom virtual scenario and to fully immerse the user in such is a powerful tool that offers immense potential for digitally enhanced variants of conventional therapy. In relation to our work, it is of particular interest to visualize customizable body parts or to let the user experience them from an immersive first-person perspective. The induction of ownership and agency could be used to address body image and perception disorders, e.g., eating disorders or CRPS but also for the treatment of PLP (Osumi *et al.*, 2019; Rothgangel and Bekrater-Bodmann, 2019) or motor imagery training (Choi *et al.*, 2020). The other application domain addressed in this dissertation is gamification, which was successfully implemented in StableHandVR. Most participants from both the evaluations of StableHandVR and PhantomAR seemed to be familiar with the concept of serious games and did appreciate it. In comparison to PhantomAR, it is apparent that the motivational elements of StableHandVR as well as the task-oriented design were effective in providing incentives for a broader range of players than the sole curiosity driven discovery in PhantomAR, which highlights the need to take into account different player types (Tondello *et al.*, 2016).

Still, both applications succeeded in putting patients into a flow state that visibly contributed to higher engagement. We further think that to achieve this state it is not necessarily advantageous to use highly immersive but more elaborate technologies such as VR or MR, since the success of engaging game mechanics is mainly dependent on their underlying persuasive strategies (Cugelman, 2013). Depending on the use case, a tablet or smartphone might be sufficient to create an engaging environment while providing higher accessibility and usability than a highly immersive but also more complex application. The value of using such technologies over conventional forms of therapy therefore is conditional and the benefits derived from a certain technology should always outweigh its complexity and cost. Usability should be prioritized over complex and expensive technologies, even if they offer appealing possibilities. In this context, the immersive VR technology provided by the Meta Quest 2 is interesting in particular because the system hides its high complexity well from the user. Nevertheless, it should be carefully considered how dependent on such technologies a system should become. Concerning the context of this dissertation, we see the greatest potential of immersive digital media applications in the visualization of body images and body parts that can be experienced from a first-person perspective.

6.4 Outlook

During the process of conceiving and developing the presented applications, we have gained insights and experience concerning the practical implementation of digital mirror therapy and the gamification of therapeutic scenarios, and with CALA, we have developed a generic and fast procedure for the creation of digital phantom limbs. With this knowledge, we can now continue where the introduction ended: with the alleviation of phantom pain through digitally enhanced mirror therapy and the virtual representation of phantom limbs. It can be assumed that the efficacy of mirror therapy is limited for some patients due to the deformed or twisted nature of their phantom limb, which cannot be represented correctly by a reflection of the intact limb or by a generic digital model (Rothgangel and Bekrater-Bodmann, 2019). Therefore, it seems reasonable to combine VR/MR mirror therapy with a customized CALA phantom to enable patients to experience an individually adjusted virtual limb from an immersive first-person perspective. This setup could be extended by a variant of graded motor imagery to further stimulate the patient's imagination. The digital limb could be made adjustable in real-time or being programmed to perform certain movements.

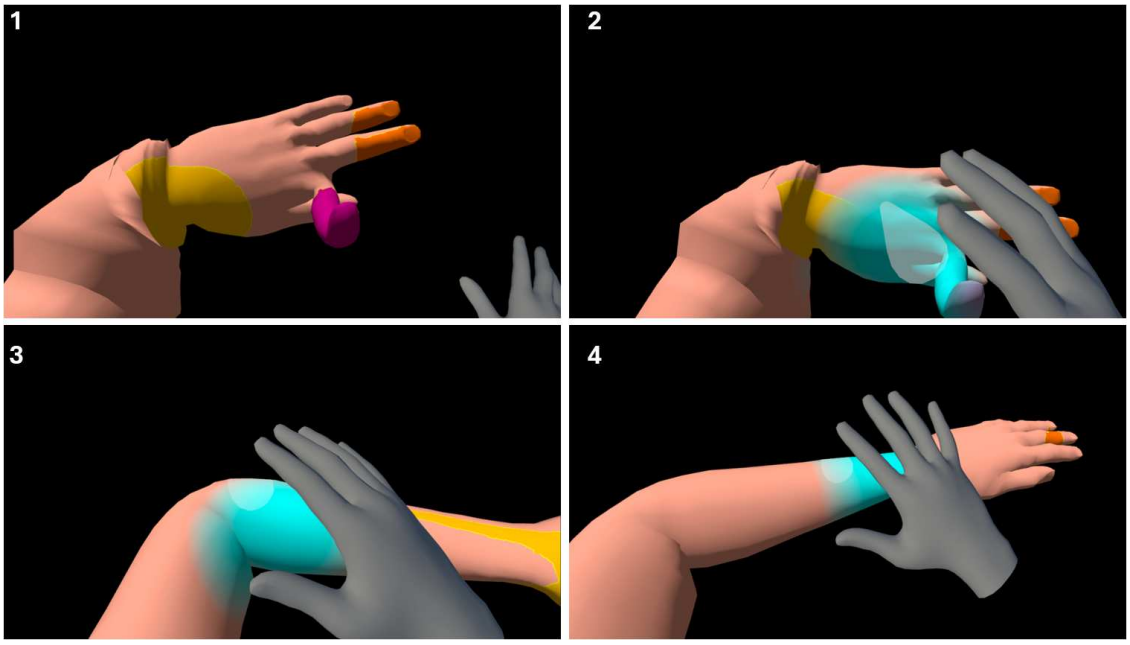

Figure 6.1: An early functional prototype visualizes a CALA limb from an immersive first-person perspective in a virtual reality setup. Stroking over the phantom limb with the healthy hand transforms it back into a normal shape and position and erases the pain painted on the skin.

Furthermore, the phantom limb could become interactable in a way that patients

could, e.g., pull their redacted limb back into the correct position with the healthy hand or use it to “heal” the distorted phantom limb (see Fig. 6.1).

To further amplify the impression, other senses could be stimulated as well, e.g., by including vibro-tactile and audiovisual feedback in the interaction. Therapeutic techniques like autogenic training, where body perception is influenced through formulas (e.g., "my right arm is warm"), could be guided by a narrator’s voice. Residual limb tracking could be improved by monitoring the orientation of the shoulder in addition to the upper and lower arm. Alternatively, for a simpler setup without additional devices, residual limb tracking could also be omitted entirely by simply mirroring the healthy hand and estimating the positions of the upper and lower arm. Another option would be to integrate the process of connecting, calibrating, and attaching the IMU sensors into the game. Finally, game mechanics such as badges or rewards could be introduced to define meaningful goals for the player and to make the tasks more appealing.

Chapter 7

Conclusion

In this dissertation 3 applications are presented that were conceived and evaluated with the purpose of supporting patients in their rehabilitation process.

CALA We investigated how phantom limbs could be captured and visualized by evaluating a prototype of such a tool. The positive resonance and the demand for such a tool, which was repeatedly expressed by therapists and amputees, led to the development of a full version of CALA. Despite the small number of participants included in the study, the knowledge that was gathered regarding the functionality and usability of the prototype was valuable for the development of the full version. While the development is still ongoing in 2025, CALA is already being used in multiple facilities across the globe and so far, has proven to be sufficient for everyday use. With CALA, we have created a tool that provides a standardized form for the documentation and representation of phantom limbs and can be used as a descriptive documentation method. Furthermore, it helps to bridge the gap between the patient's perception and the therapists' understanding of phantom limbs and facilitates the process of quantifying and monitoring the change of the phantom limb over the course of therapy.

StableHandVR We investigated the use of a standalone immersive VR HMD in a therapeutic context and the design and implementation of gamification strategies for hand therapy. The resulting game was positively received by the patients and could effectively provide a motivating environment. The iterative development approach proved to be effective to incorporate feedback from patients and therapists and contributed to shape a positive and flawless user experience. The Meta Quest 2 HMD proved to be user-friendly and easy to operate and rendered the application sufficient for practical use in a clinical or therapeutic setting. Furthermore, it confirmed the potential of such mobile and accessible VR technology for everyday practical use in a therapeutic setting. In conclusion, StableHandVR serves as a solid foundation for the further development of a wholesome hand and finger rehabilitation game that could ensure long-term engagement.

PhantomAR We created an immersive MR application that enhances mirror therapy by providing a freely explorable and interactive environment and an augmented virtual hand that can be used together with the real hand. The spatial mapping of the HoloLens 2 proved to be an excellent feature for the dynamic generation of scenarios that are embedded in the real world. PhantomAR was positively received by the patients, clinically effective in alleviating PLP and could induce a high sense of embodiment for the virtual arm. However, the cumbersome user experience of the HoloLens 2 might have impaired the usability of the application and attenuated the measured effects, and a precondition for an improved user experience might be to abandon the HoloLens 2 in favor of a more user-friendly device. In conclusion, PhantomAR offers an immersive MR experience that extends the limitations of traditional mirror therapy and could serve as a bridge during the rehabilitation process for the phase after the amputation, while the residual limb is healing and before a real prosthesis can be fitted.

In summary, all applications can be considered to be successfully conceived and implemented for their respective purpose. The close cooperation with physiotherapists, doctors and patients enabled an in-depth elaboration of the requirements and ensured the development of tailor-made and user-friendly digital tools. Thereby, we see a particular advantage in the use of immersive digital media for simulating altered body images. The gained knowledge and the core elements of the developed applications can further be combined to create a new form of digital mirror therapy: The use of a CALA phantom, visualized in an immersive and gamified MR/VR environment, and adjustable by the patients in real-time, represents a promising starting point for further research regarding the alleviation of PLP and underlying mechanisms.

Appendix A

Publications Contained in this Thesis

A.1 Publication I

frontiers in Rehabilitation Sciences

ORIGINAL RESEARCH
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Visualizing the Unseen: Illustrating and Documenting Phantom Limb Sensations and Phantom Limb Pain With C.A.L.A.

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Currently, there is neither a standardized mode for the documentation of phantom sensations and phantom limb pain, nor for their visualization as perceived by patients. We have therefore created a tool that allows for both, as well as for the quantification of the patient's visible and invisible body image. A first version provides the principal functions: (1) Adapting a 3D avatar for self-identification of the patient; (2) modeling the shape of the phantom limb; (3) adjusting the position of the phantom limb; (4) drawing pain and cramps directly onto the avatar; and (5) quantifying their respective intensities. Our tool (C.A.L.A.) was evaluated with 33 occupational therapists, physiotherapists, and other medical staff. Participants were presented with two cases in which the appearance and the position of the phantom had to be modeled and pain and cramps had to be drawn. The usability of the software was evaluated using the System Usability Scale and its functional range was evaluated using a self-developed questionnaire and semi-structured interview. In addition, our tool was evaluated on 22 patients with limb amputations. For each patient, body image as well as phantom sensation and pain were modeled to evaluate the software's functional scope. The accuracy of the created body image was evaluated using a self-developed questionnaire and semi-structured interview. Additionally, pain sensation was assessed using the SF-McGill Pain Questionnaire. The System Usability Scale reached a level of 81%, indicating high usability. Observing the participants, though, identified several operational difficulties. While the provided functions were considered useful by most participants, the semi-structured interviews revealed the need for an improved pain documentation component. In conclusion, our tool allows for an accurate visualization of phantom limbs and phantom limb sensations. It can be used as both a descriptive and quantitative documentation tool for analyzing and monitoring phantom limbs. Thus, it can help to bridge the gap between the therapist's conception and the patient's perception. Based on the collected requirements, an improved version with extended functionality will be developed.

Keywords: limb amputation, phantom limb sensation, phantom limb pain, body image visualization, altered body image, documentation methodology, digital assessment, software tool

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INTRODUCTION

After the amputation of a limb, up to 90% of the patients report a feeling of the missing body part still being present (1). This effect is known as phantom limb sensation (PLS) and ranges from the simple feeling of presence to the perception of a specific posture, shape, or involuntary movements of the amputated limb (2–4). Additionally to PLS, which is defined as any sensation except pain (3), 45–85% of all patients suffer from phantom limb pain (PLP), which can manifest itself as e.g., stabbing, burning, twisting, or cramping (5). The term "phantom pain syndrome" was coined by Weir Mitchell in 1871 (4) when the use of the word "phantom" was commonly used in the medical field to describe pseudo-diseases, which may have contributed to the fact that PLP was stigmatized as "imaginary" for a long time (6).

PLP usually manifests itself 24 h to 1 week after amputation and decreases in intensity and frequency over time in most patients (3). Especially in the distal areas of the missing limb, PLP as well as PLS generally persist the longest. Some patients suffer from this pain for decades (2, 7). The underlying mechanisms causing PLP and PLS are still discussed controversially. The current dominant theory is the cortical remapping theory, according to which the brain responds to the loss of a limb with the reorganization of somatosensory maps: cortical areas that have received sensory signals from the amputated limb begin to receive input from neighboring areas (2, 4). Another explanation is based on the concept of a "neuromatrix"—an internal representation of one's own body. After an amputation, this representation remains intact and no longer matches the actual body, thus causing pain. The absence of visual and sensitive feedback of the missing limb enhances this effect (8).

PLP, defined as painful sensation in the missing part of the limb, is to be distinguished from pain in the residual limb (9), and in particular from neuroma pain. Painful neuromas develop at the stump of the severed nerve due to misguided attempts of nerve regeneration and are one of the main causes of residual limb pain (4, 10). Physical stimulation of the neuroma in form of pressure or stress on the limb can increase PLP, and in the past, neuromas were considered to contribute to the development and maintenance of PLP. However, PLP does also occur in the absence of stump pain, and removal of a neuroma does not cause PLP to disappear (2, 3).

PLP is an elusive entity, which makes it hard to track the progress of these patients over the course of treatment. Currently, there is no standardized mode of documenting PLP and PLS. The guidelines of the German Society of Neurology for the diagnosis of neuropathic pain recommend to document the onset and duration, the temporal course, pain qualities, localization and intensity as well as factors triggering pain (11). In general, it has become common practice to survey phantom pain with pain questionnaires. For example, the McGill Pain Questionnaire (MPQ) (12) became a de facto standard for the qualitative characterization of PLP, which is reflected by the terminology used in the medical literature after 1975 (13). Other pain questionnaires, such as the Brief Pain Inventory (BPI) (14), allow for the localization of pain by marking the appropriate areas on a 2D body chart. However, this type of documentation has the disadvantage of being not very precise. Shaballout et al. showed that a digital solution for drawing pain can not only contribute to a better understanding of the pain situation for physicians, but also facilitate analysis and quantification (15). Further improvement in the precision of this approach could be achieved by drawing pain directly on a 3D model (16).

This still does not allow for the illustration of the patients' altered body image, in particular the phantom. Although several software tools do exist that can be used to illustrate an altered body image, these have been developed primarily in the context of eating disorders (17–19). Therefore, the specific representation of a phantom limb is not possible with this approach. Appropriate illustrations would require an artist guided by the patient or could be drawn by patients with the appropriate drawing or photo editing skills (20). However, this is costly and totally unfeasible in a clinical context. Furthermore, it does not allow for a quantifiable analysis.

Since we could not find any suitable software, we decided to develop such a tool ourselves. In the present study we describe the functionality of the first version of C.A.L.A. (Computer Assisted Limb Assessment) and the results of its evaluation with therapists and patients in terms of usability and functionality.

MATERIALS AND METHODS

C.A.L.A.

The basic idea of C.A.L.A. is the customization of a virtual human 3D avatar in such a way that it represents the patient's body image including their PLS. A prototype (21) and a first version of C.A.L.A. were created by modifying and expanding the Open Source software applications MakeHuman (22), a software tool for 3D character creation, and the 3D modeling software Blender (23). This first version provided a 3D avatar that could be freely rotated and viewed from all sides and the principal functions of C.A.L.A.: (1) General adjustment of the 3D Avatar; (2) altering the shape of the phantom limb; (3) positioning the phantom limb; (4) drawing pain and cramps; and (5) the quantification of the created body image.

The process of documenting a patient over the course of treatment was as follows: Initially, a basic model is created by adjusting the 3D avatar to fit the patient's (perceived) body dimensions. This model then serves as a baseline to be built on in the following sessions. Over the course of treatment, the phantom limb can then be adjusted in terms of deformation, position, and pain, thus visualizing the changes in perception by the patient.

These functions are explained in detail in the following:

Adjusting the 3D Avatar

To increase the patient's identification with the 3D avatar, we used some of the original functions provided by MakeHuman, which allow for the adjustment of the avatar in terms of gender, age, muscles, weight, and proportions. These adjustments have no further purpose in the documentation process apart from cosmetic ones. The avatar can additionally be clothed with underwear.

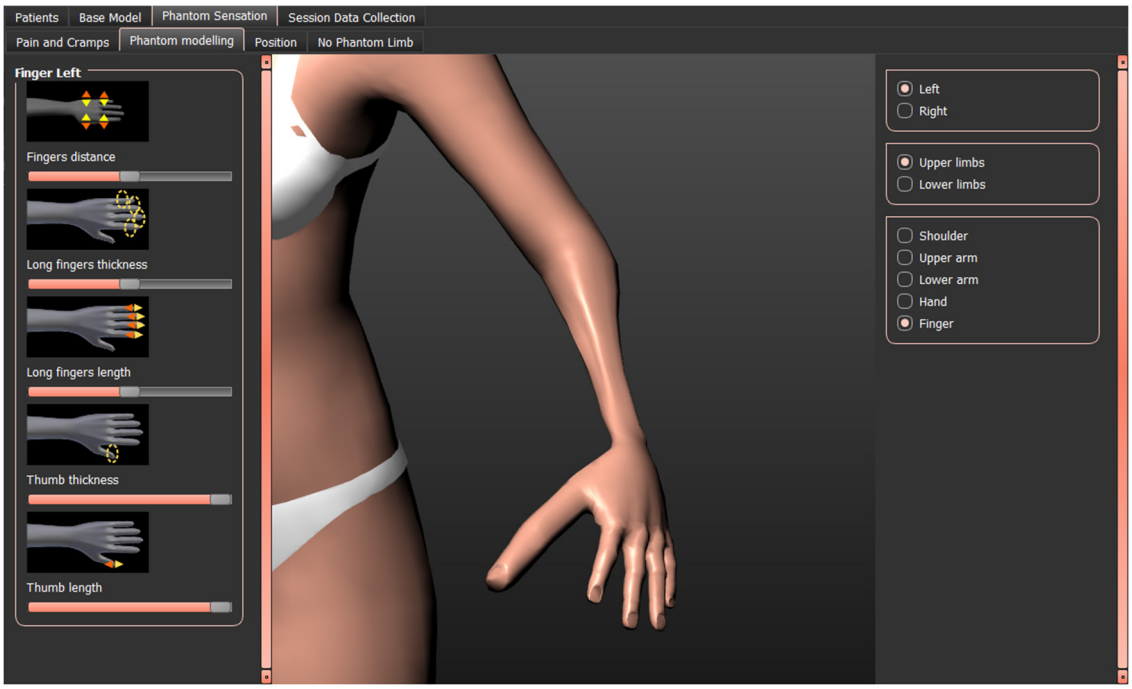

FIGURE 1 | Adjusting the shape of the phantom limb by decreasing the thickness of the lower arm and increasing length and thickness of the thumb.

Measuring the Patient

The patient's body measurements can be transferred to the avatar. The body height as well as circumference and length of upper arm, forearm, upper and lower leg, fingers, and toes as well as the length and width of hands and feet can be entered and form the basis for the subsequent measurements of the phantom limb.

Modeling the Phantom Limb

The length and circumference of the upper arm, forearm, thigh, and lower leg can be increased or decreased. Hands and feet can be enlarged or shrunk. Fingers and toes can be adjusted in length and circumference, the thumb and long fingers can be adjusted separately. The telescoping effect can be represented using this feature (see **Figure 1**).

Positioning the Phantom Limb

The sensation of the phantom limb being fixed in one or more, twisted or unnatural positions is captured by moving the respective joints of the 3D avatar into the position reported by the patient. Based on the original MakeHuman 3D model, it is possible to rotate the shoulder, elbow, and wrist joints as well as the individual finger joints of the 3D avatar, the same applies to the joints of the lower extremities. All joints can be rotated along their natural axes in steps of $\pm 10^{\circ}$ and even beyond the limits that are anatomically possible. As a result, all conceivable positions of the upper and lower extremities can be represented (see **Figure 2**).

Drawing Pain and Cramps

Pain is drawn directly onto the 3D avatar by using the mouse cursor as a brush, similar as it is done in 2D paint software. Currently C.A.L.A. distinguishes between pain in general and cramps in the phantom, these two aspects can be drawn independently of each other and with their respective intensity (see **Figure 3**), which is indicated by the Numeric Rating Scale (NRS) with a value between 0 and 10. The intensity is represented by different color schemes, general pain by a color gradient from yellow (slight pain) to dark red (severe pain), cramps by a color gradient from light blue (slight cramping) to dark blue (severe cramping).

Quantifying the Body Image

All data that were entered during the documentation process can be quantified and contain informative value about the phantom's constitution at the respective time. This allows for the analysis of the recorded aspects, namely deformation, position, and pain, and for their observation over the course of treatment. The quantification of these three aspects is briefly described as follows: Quantification of deformation reflects the percentage change in length and circumference of the respective limbs compared to the base model. Based on the originally collected dimensions of the patient's body, these changes can also be expressed absolutely in centimeters. The quantification of the position results from the deviation of each rotation axis of each joint from the basic position of the 3D avatar. Pain and cramps are quantified as the percentage of the body surface that is covered by the respective intensity.

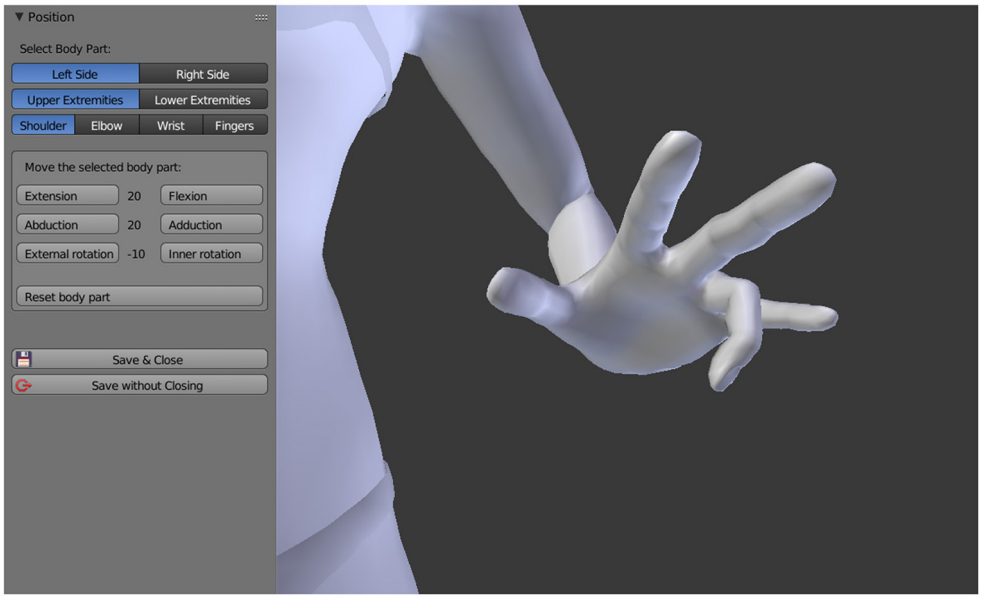

FIGURE 2 | Adjusting the position of the phantom limb by rotating the respective joint axes.

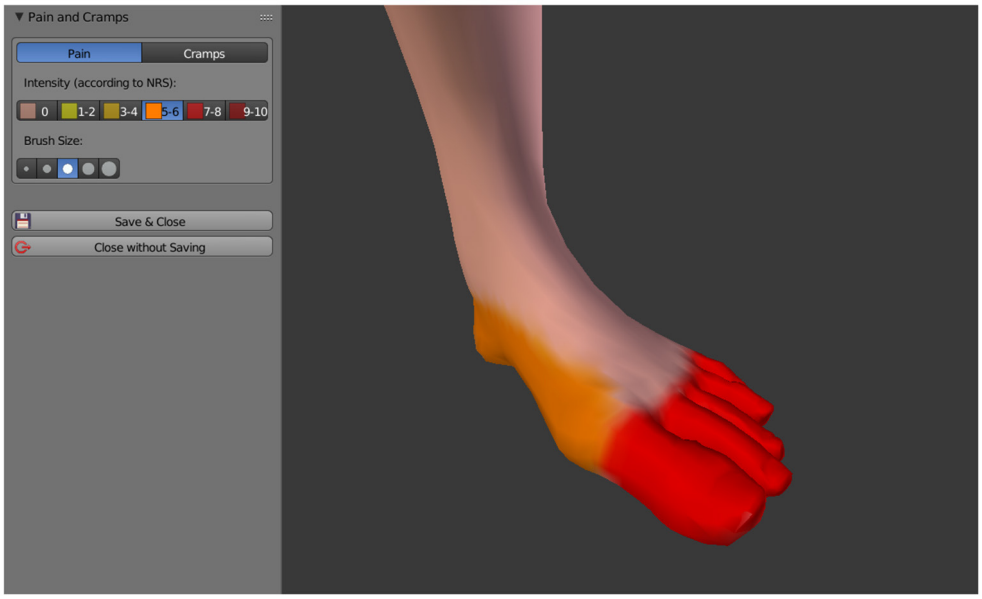

FIGURE 3 | Pain drawn directly onto the 3D avatar in different intensities.

Participants: Evaluation With Therapists

C.A.L.A. was evaluated with 33 professionals (19 physical therapists, 9 occupational therapists, 2 orthopedic technicians, 3 medical staff). Of these, 22 were female and 11 were male with an age range of 25–58 and a mean age of 41. The inclusion criteria for all participants were to actively work with amputees and document their phantom limb in a clinical context.

Each participant was initially provided with a brief introduction to the operation of C.A.L.A. Subsequently, participants were given the task to perform the entire documentation process (see Section C.A.L.A.) on two given, fictional patients (see **Supplementary Material**). These tasks were the same for all participants. It included the creation of a basic model, adjustment of the phantom's deformation, adjustment of the phantom's position, and

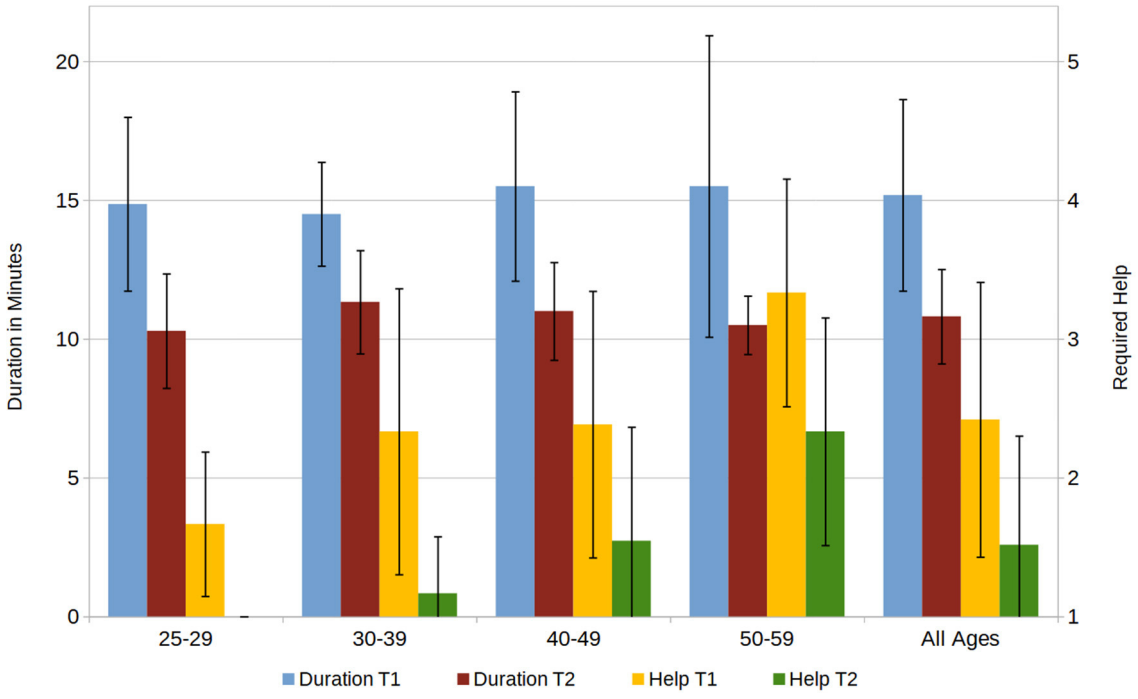

FIGURE 4 | Required duration for completion of the first and second task (T1, T2) in minutes and the required assistance, rated on a 1–5 Scale (1 = "no help," 5 = "a lot of help").

finally drawing pain and spasms. All participants were observed while performing the tasks and provided with assistance in operating the software. The duration for completing each task was measured and the level of assistance required was rated on a 1–5 Likert Scale by the investigator.

Subsequently, all participants were questioned with the System Usability Scale (24) to determine the user-friendliness of the software. With an additional self-developed questionnaire (see **Supplementary Material**) and semi-structured interview, the therapist's methods of documenting phantom pain and phantom sensation were surveyed and the principal functions of C.A.L.A. were rated. In the semi-structured interview, difficulties regarding the use of C.A.L.A., suggestions for improvement and additional desired functionalities as well as application scenarios were collected.

Participants: Evaluation on Patients

To test the scope of the currently implemented functionality regarding real-world cases of PLS and PLP, we evaluated C.A.L.A. on 22 patients with the following amputations: 1× transhumeral, 1× transradial, 12× transfemoral, and 5× transtibial, thereof one patient with a transfemoral and one with a transtibial amputation of both legs, 3× finger amputation. Eight of the patients were female and 14 were male with an age range of 21–73 and a mean age of 52. The inclusion criterion for all patients was the amputation of at least one limb.

For each patient, the entire C.A.L.A. documentation process was performed (see Section C.A.L.A.) by the investigators. The therapists who took part in our study did not evaluate the patients. Subsequently, the patients were questioned about their phantom pain with the German version of the Short Form McGill Pain Questionnaire (SF-MPQ-D) (25) to assess the presence of the different pain qualities. We administered a self-developed questionnaire (see **Supplementary Material**) with a 1–5 Likert scale rating system ("very inaccurate" to "very accurate") to determine how accurately the patients rated the representation of deformation, position, and pain of their phantom, and which aspects could not be mapped.

RESULTS

Evaluation With Therapists

All 33 participants completed the documentations of two given fictional patients. The average duration needed to complete a task decreased from 15.2 (±3.5) min for the first task (T1) to 10.8 (±1.7) min for the second (T2), the assistance provided by the investigator, measured on a 1–5 Likert scale ("very little help" to "very much help"), decreased from 2.4 (±1.0) to 1.5 (±0.8). Broken down by age group, the duration was very similar through all groups, however the amount of help provided was the highest for the oldest age group and the lowest for the youngest age group (see **Figure 4**).

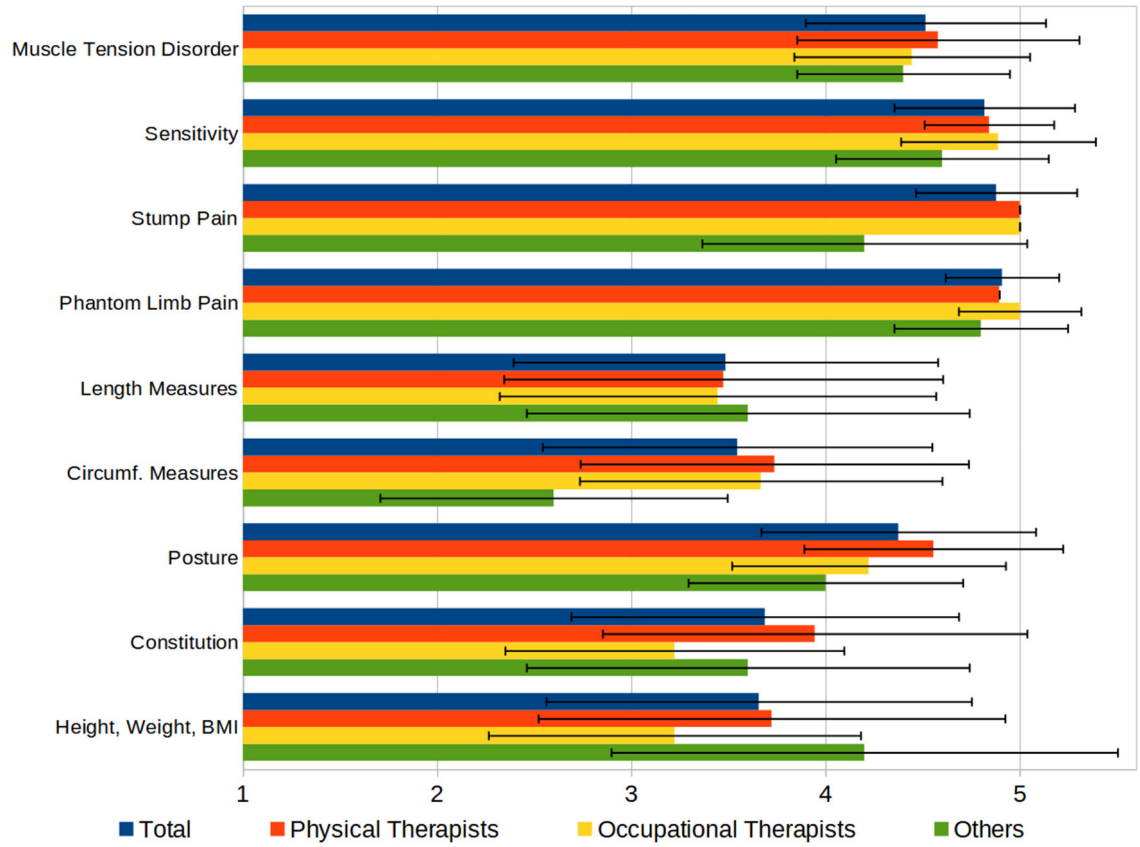

FIGURE 5 | Aspects of a therapeutic finding, rated by importance on a 1–5 Scale (1 = "not important," 5 = "very important").

The evaluation with the System Usability Scale resulted in an average score of 81.7% (±11.2), placing in the 4th quartile which represents high usability. The values are similar across age groups and professions. Additionally, we evaluated the usability of C.A.L.A. by user observation and semi-structured interviews, in which we asked about the difficulties in using C.A.L.A. Several users mentioned that the controls were too small and too cluttered. We also observed operational errors (such as modifying the wrong side of the body), problems understanding the user interface and difficulties navigating the 3D avatar.

With a separate, self-developed questionnaire and semi-structured interview we prompted the participants about their own documentation methods during therapy. Regarding the use of templates or specific questionnaires, 45% of the participants reported to use body charts to draw pain and 27% use validated questionnaires to assess pain, PLS, or body image. Besides questionnaires, the documentation was usually mostly handwritten and in a self-defined form.

We asked the participants to rate various aspects of the therapeutic finding by their importance on a scale from 1 to 5 ("not important" to "very important"). The results (see **Figure 5**) show the high importance of pain, sensation, and muscle tension, compared to the measures of the patient's body or their physical condition.

Regarding the documentation of pain, most of the participants (76%) used the Numeric Rating Scale (NRS) and 51% used the Visual Analog Scale (VAS) (26) to assess the intensity of pain. Twenty-four percent of the participants used pain questionnaires, with no questionnaire being reported more than once. Other aspects of pain such as influencing factors (e.g., medication, psychological state), temporal (24-h) course, and duration are documented in a free form. Questioned about the importance of several aspects of pain in documenting rated on a 1–5 scale ("not important" to "very important") showed that in average all aspects have been rated above 4.5 (see **Figure 6**).

Subsequently, we asked the participants to evaluate the functionality of the C.A.L.A. features. Using a Likert scale from 1 to 5 ("very low" to "very high"), participants were asked to rate the usability of the functionalities regarding the documentation of phantom limbs on a 1–5 scale ("not helpful" to "very helpful"), which resulted in high acceptance of the functions, rated least was the function to quantify the deformation of the phantom with 3.6 (±1.2) (see **Figure 7**).

In the semi-structured interview, we asked about additional functionalities for C.A.L.A., the most frequently mentioned ones are listed as follows: The documentation of pain qualities and the temporal aspects of pain (course, duration, frequency) were

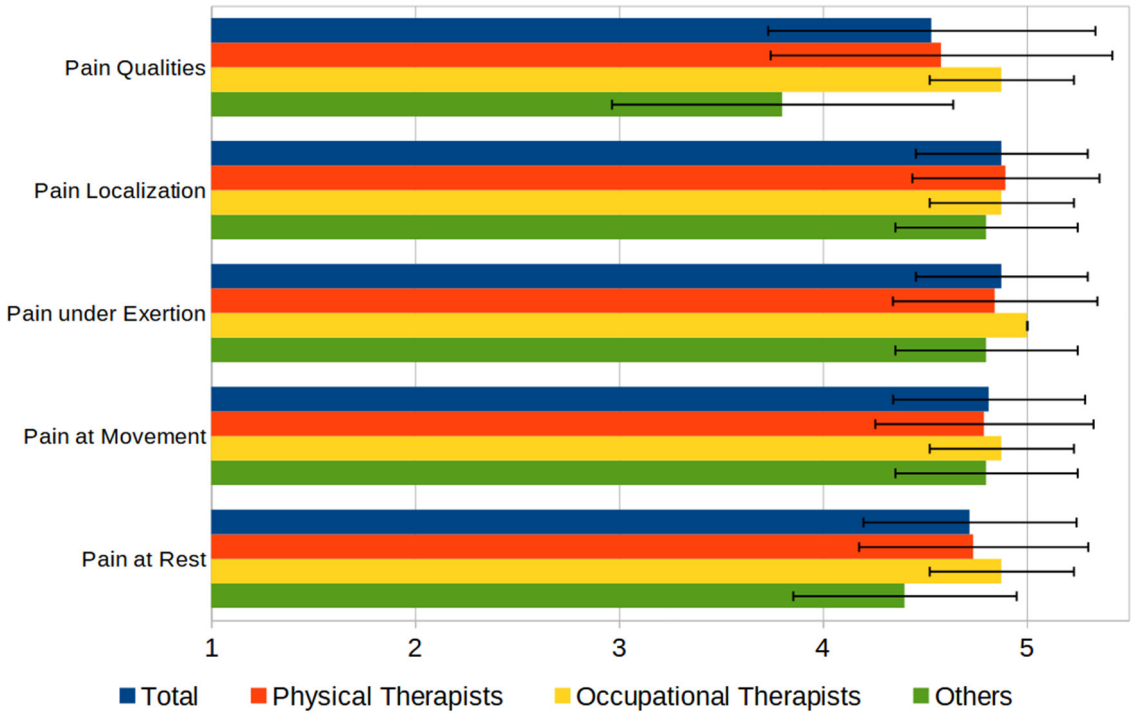

FIGURE 6 | Aspects of documenting pain, rated by importance on a 1–5 Scale (1 = "not important," 5 = "very important").

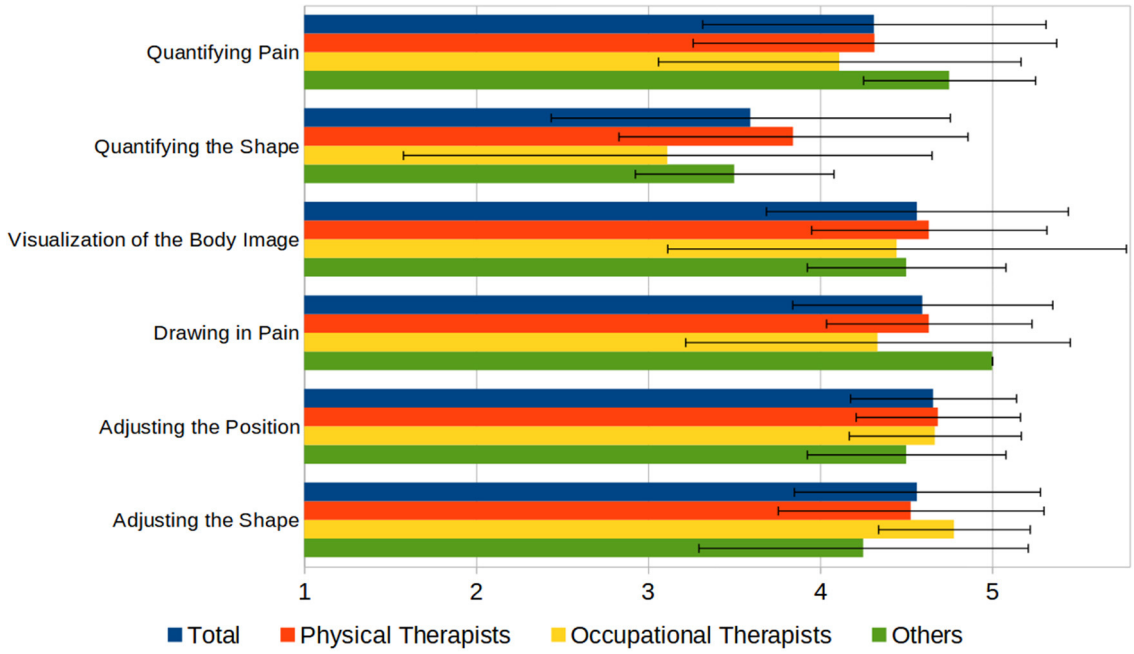

FIGURE 7 | Principal functions of C.A.L.A., rated by usefulness on a 1–5 scale (1 = "not useful," 5 = "very useful").

mentioned very frequently, not only in relation to phantom pain but also to residual limb pain. Another request concerned the modeling and positioning of the body parts, here a more differentiated adjustment, especially of the fingers and toes, was asked for. Regarding the positioning of the phantom, it was suggested to use a standardized diagnostic specification to

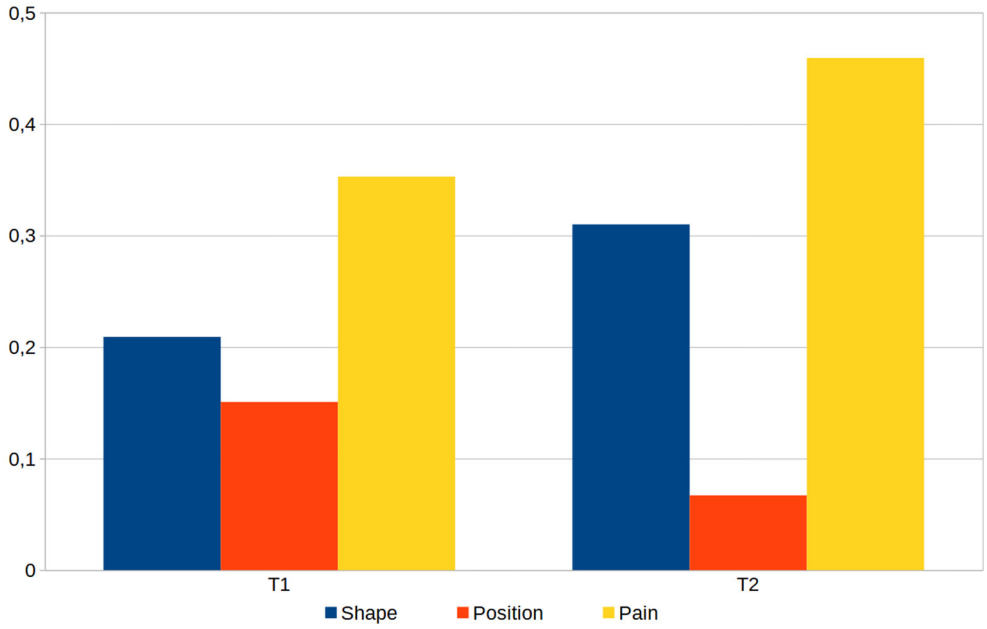

FIGURE 8 | The averaged coefficient of variance calculated for the three main aspects shape, position and pain, as determined from all 33 generated models for task 1 (T1) and task 2 (T2) of the therapist evaluation.

describe the rotation of the joints, e.g., the deviation from the neutral zero position (27).

Finally, we compared the quantifiable aspects of the documentations that have been created in the first respective second task by all participants, namely the shape and position of the phantom, and the drawing of pain and cramps. Analyzing the data revealed that during the documentation of both tasks, 3—always different—participants mixed up the side of the body and worked on the wrong arm or foot. The data of these six documentations were corrected by the side of the body and added to the evaluation. We determined the coefficient of variance for all parameters of the respective documentation aspects (deformation, position, and pain) and calculated their mean values (see **Figure 8**). This shows the smallest deviations when setting the position and the largest deviations when drawing pain, which is true for both tasks.

Evaluation on Patients

Seventeen of the 22 patients were experiencing PLP, five of them reported a deformed phantom and five reported a twisted position of the phantom. Thirteen patients reported suffering from stump pain.

All 17 patients with PLP or a deformed or twisted phantom were asked how well their phantom and their body image could be mapped, rated on a 1–5 Likert scale ("very inaccurate" to "very accurate"). The other five patients, who only reported stump pain were just asked about the accuracy of their body image representation. The phantom was rated with an average of 4.6 (±0.7), the body image with 4.2 (±1.0). We also asked the patients, how important the aspects of gender, age, and physical shape were for them regarding the accurate representation of body image, which revealed that these aspects were not of primary concern.

Regarding the functional range, it was often remarked that the body image was inaccurate due to the missing visualization of the residual limb. Modeling of the individual fingers was required in greater detail than provided, both in terms of deformation and position. It was also not possible to visualize, that some parts of the amputated limb were still present as phantom sensation while other parts were no longer perceived.

The documentation of pain revealed the missing option of documenting different qualities of pain. Here, especially the pain quality "stabbing" was mentioned several times. Another functional absence was the description of the temporal aspects of pain, such as long, short, or periodic pain. In addition, patients mentioned various other aspects when describing their pain, such as the course of the pain experience, the time of day, whether the patient was resting or moving, or even the influence of weather.

Subsequently, all 22 patients were interviewed with the SF-MPQ-D to measure number of pain qualities mentioned per patient and the frequency of each pain quality. For the patients without phantom pain, stump pain was queried instead. On average, 4.8 (±2.8) of 15 qualities were mentioned per patient, the most frequently mentioned were "shooting," "stabbing" and "hurting." During the interview as well as during the documentation of pain in C.A.L.A., it became apparent that the distinction between stump and phantom pain was not clear for many patients and therefore a mixture of both pain sensations was sometimes described.

DISCUSSION

Advantages of C.A.L.A.

The evaluation of C.A.L.A. with the System Usability Scale and the survey have shown that the vast majority of the participants considered C.A.L.A. user-friendly and feasible. To our knowledge, there is currently no software tool for therapists that allows for the visualization of phantom limbs, especially considering deformation, position, and pain. Therefore, rendering a comparison of C.A.L.A. to any existing standard regarding the documentation of phantom limbs is practically impossible. In a clinical setting time is of the essence. The duration of the documentation averages at 10 min, reducing the time by about one third in the second documentation trial, indicating that more training will likely reduce the time further.

During the evaluation with patients, they reported of never having given this amount of thought to the exact nature of their phantom limb. This fact was especially observable in localizing PLP. It was stated in only one case that the process of visualizing the phantom had a negative impact on the patient's body image. No patient indicated that phantom pain had increased because of the documentation process.

In this study we emphasized validity and did not specifically test for reliability, due to the nature of the modeling and positioning of the phantom limb and pain, which is dependent on the accuracy of the patient's report. We have provided different levels of detail in the tasks for position, deformation and pain, which is supported by the documentation differences shown in **Figure 8**. Especially regarding pain, room was intentionally left for interpretation, mimicking actual interactions with patients. In doing so, pain drawing could be assessed which resulted in the high variance. Corrective interventions during the dialogue with the patient could have lowered the outcome in variance.

Since all body image data are available in digital form, they can be easily quantified. This allows for a much more precise and simpler quantification than it would be possible with the conventional, mainly analog, methods. The amount of pain drawn onto a 2D human outline as well as joint angles of the phantom could possibly be estimated as could the circumference and the length. However, to our knowledge no one has ever calculated such values, especially regarding position and deformation, nor have their changes been evaluated over the course of treatment. To the best of our knowledge, no tools exist, yet, which can be used to document phantom limbs and PLP. C.A.L.A. offers a convenient tool to document just that.

In addition to evaluating usability, an essential aspect of our study was to identify possible extensions and adaptations of the functional scope. These will be discussed as follows.

The Struggle With Documenting Pain

When documenting PLP and PLS, pain is clearly the most important issue. Pain affects the patients' quality of life, and its reduction usually is the primary goal of therapy. The importance of pain was also evident in the qualitative surveys with patients, in which it was described by far the most frequently and in the greatest detail. In the therapist survey, too, there was the most feedback on the topic of pain documentation.

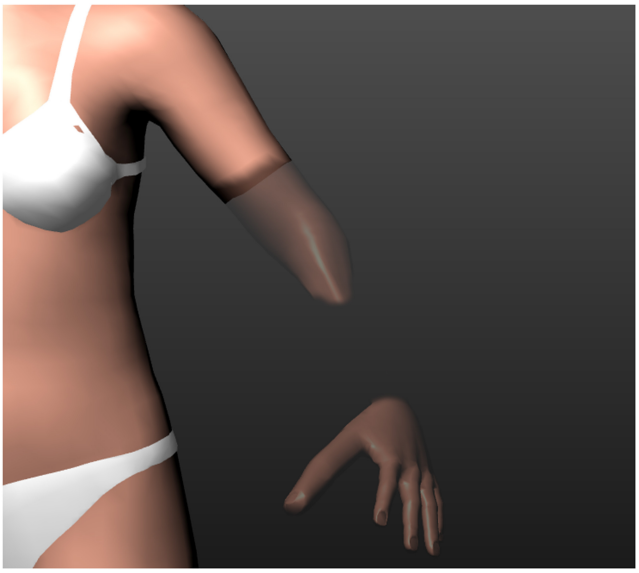

FIGURE 9 | A conceptual illustration of how to visualize the residual limb and phantom limb. The "presence" of the phantom limb is indicated by its visibility, meaning that the invisible parts are no longer perceived by the patient.

In this context, the topic of pain qualities was most frequently mentioned by both patients and therapists. This is not surprising since using these pain qualities for describing PLP had been established almost 50 years ago (13). Currently, in C.A.L.A. it is only possible to enter "general" pain and the pain quality "cramping." Expanding this to document other pain qualities seems useful, whereby clustering them to a few 5–10 qualities would be necessary. The current method of evaluating the pain intensity using the NRS is a common approach among the interviewed therapists (used by 76%).

In addition to the localization, intensity and the qualities of pain, the guidelines of the German Society of Neurology (11) recommend documenting the aspects of duration and temporal course as well as the factors that trigger pain. In addition, the qualitative evaluation also revealed quite a few other aspects of pain relevant for a complete description, e.g., deep/superficial pain. However, all mentioned aspects have in common that their visualization in C.A.L.A. would be difficult and not very intuitive to understand. We therefore consider it useful to omit these aspects from the documentation of PLP in C.A.L.A.

Representation of Phantom and Stump

Besides the issue of pain, C.A.L.A. should include means of clearly visualizing the stump to make it easier to distinguish it from the phantom. Several patients stated during the qualitative interviews that the visualization of their body image was not complete due to the missing visualization of the stump, even if the sensation of the phantom limb was present in the patients.

When drawing PLP based on the patients' descriptions, it became obvious that the strict distinction between phantom pain (exclusively in the missing part of the limb) and stump pain

(exclusively in the part still present) (9) was not necessarily useful for the patients. Although we pointed out that we intended to document only phantom pain, in some cases the pain described extended from the phantom to the existing limb, in a few cases even to the middle of the body.

The distinction between PLP and residual limb pain could be simplified in a future version of C.A.L.A. by a clear visual differentiation between residual limb and phantom limb in the representation of the 3D avatar (see **Figure 9**). This would make it more obvious, both when drawing and when evaluating pain, whether the pain is located at the stump or actual PLP is experienced. Considering that pain in general is probably the most important aspect of quality-of-life-limiting discomfort, we consider it useful to expand C.A.L.A. to include the documentation of stump pain as well.

As described in the literature (2, 20) and also observed in some patients, phantom sensation was not present in the entire lost limb, but only in the distal areas of the phantom. To increase the precision of the representation, this circumstance could be represented by masking the areas of the phantom that are no longer perceived (see **Figure 9**).

Adjusting the Functionality

In addition to these two main topics, we have identified several other contexts in which C.A.L.A. could be improved to increase its usability and validity. The most relevant ones are listed below.

When adjusting the position of the phantom limb, the 3D avatar is initially in a position where arms and fingers are slightly spread and bent. While this body position is advantageous for painting and deforming the phantom, we think that a more standardized body position, such as the neutral-zero position (27), would be more beneficial for phantom limb positioning. We believe that such an alignment of the initial position will not only facilitate the positioning of the phantom, but will also increase the significance of the quantified position. The range of functions concerning the positioning and deformation of the phantom has shown that the currently provided options can only partially cover the large variety of different perceptions. Especially for hand and fingers, but also for foot and toes, it would be required to allow adjusting them in further detail.

Another feature that has been mentioned several times was the desire for a visual representation of the progress of the phantom over the course of treatment; or, in other words, over the course of several documentations. This could especially help both to clearly demonstrate the progress of therapy and to motivate the patients to continue.

Finally, participants also considered other possible application scenarios in which C.A.L.A. could be used with modified functionality. Often mentioned was the application in Complex Regional Pain Syndrome (CRPS) or stroke patients, as well as for all other situations in which patients experience an altered body image.

CONCLUSIONS

We have created a tool that allows for the visualization and documentation of PLP and PLS. Thus, it provides a standardized form for their presentation and can be used as a descriptive and quantitative documentation method.

Based on the evaluation with the therapists, a great demand for our tool could be determined, therefore a further development of C.A.L.A. is reasonable and can contribute to increase its usability and efficiency in operation. For such an improved version, the most important additional features in our point of view are briefly listed here again: (1) introduction of pain qualities; (2) clear distinction between phantom and residual limb; (3) additional documentation of residual limb pain; (4) more precise adjustment of shape and position of individual fingers; and (5) a visualization of the course of treatment over several sessions.

C.A.L.A. can help to bridge the gap between the therapist's conception and the patient's perception of the phantom limb. The possibility to quantify the representation of the phantom offers a previously unavailable option to monitor and analyze its change over the course of treatment and can help to create insights into the correlation between certain forms of treatment and PLS or PLP. Finally, C.A.L.A. enables a more integrated representation of the phantom than is possible with conventional visualization methods with little effort regarding time and other resources, increasing feasibility regarding clinical context.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Committee of the Medical Faculty of the Eberhard-Karls-University Tuebingen. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

MB designed and implemented the first version of C.A.L.A., conceived and performed the evaluation, analyzed the data, and wrote the manuscript. JM contributed to the design of C.A.L.A., contributed to planning and performing of the evaluation, and revised the manuscript. JH provided feedback on and verified the data analysis and revised the manuscript. MVB contributed to the interpretation of the results and revised the manuscript. AD and JK contributed to critical revision of the intellectual content and approved the final version. CP conceived the original idea of the project, contributed to the design of C.A.L.A., contributed to data acquisition, revised the manuscript, and was in charge of overall direction and planning. All authors provided critical feedback and helped shape the research, analysis, and manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fresc.2022.806114/full#supplementary-material

A supplementary video explaining and illustrating the functionality of C.A.L.A. can be found here: https://www.playbionic.org/cala/.

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A.2 Publication II

Original Paper

A Virtual Reality Serious Game for the Rehabilitation of Hand and Finger Function: Iterative Development and Suitability Study

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Abstract

Background: Restoring hand and finger function after a traumatic hand injury necessitates a regimen of consistent and conscientious exercise. However, motivation frequently wanes due to unchallenging repetitive tasks or discomfort, causing exercises to be performed carelessly or avoided completely. Introducing gamification to these repetitive tasks can make them more appealing to patients, ultimately increasing their motivation to exercise consistently.

Objective: This study aims to iteratively develop a serious virtual reality game for hand and finger rehabilitation within an appealing and engaging digital environment, encouraging patient motivation for at least 2 weeks of continuous therapy.

Methods: The development process comprised 3 distinct stages, each of which was subject to evaluation. Initially, a prototype was created to encompass the game's core functionalities, which was assessed by 18 healthy participants and 7 patients with impaired hand function. Subsequently, version 1 of the game was developed and evaluated with 20 patients who were divided into an investigation group and a control group. On the basis of these findings, version 2 was developed and evaluated with 20 patients who were divided into an investigation group and a control group. Motivation was assessed using the Intrinsic Motivation Inventory (IMI), while the application's quality was rated using the Mobile Application Rating Scale and the System Usability Scale. User feedback was gathered using semistructured interviews.

Results: The prototype evaluation confirmed the acceptance and feasibility of the game design. Version 1 significantly increased motivation in 2 IMI subscales, *effort* ($P<.001$) and *usefulness* ($P=.02$). In version 2, a significant increase in daily performed exercises was achieved ($P=.008$) compared to version 1, with significantly higher motivation in the IMI subscale *effort* ($P=.02$). High Mobile Application Rating Scale scores were obtained for both versions 1 and 2, with version 2 scoring 86.9 on the System Usability Scale, indicating excellent acceptability. User feedback provided by the semistructured interviews was instrumental in the iterative development regarding improvements and the expansion of the playable content.

Conclusions: This study presented a virtual reality serious game designed for hand and finger rehabilitation. The game was well received and provided an environment that effectively motivated the users. The iterative development process incorporated user feedback, confirming the game's ease of use and feasibility even for patients with severely limited hand function.

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KEYWORDS

video games; virtual reality; exercise therapy; physical therapy; hand rehabilitation; finger rehabilitation

Introduction

Background

Our hands are essential tools for managing daily life and are thus at high risk of injury. Therefore, comprehensive and successful rehabilitation to quickly restore hand function is essential for patients' quality of life and ability to work. A key factor in successful rehabilitation is to maintain patients' motivation to conscientiously participate in the process [1]. However, this is complicated by the fact that as part of their therapy, patients may experience pain reactions during or after exercise and must endure them. In addition, long-term repetitive activities are often monotonous and tend to be performed more and more carelessly without the supervision of an occupational therapist or physiotherapist [2]. However, to achieve the best possible outcome of the therapeutic process, it is necessary for patients to perform their exercises regularly, usually even daily [3,4].

In the last decade, serious games for health have become more popular and have shown a positive effect on the rehabilitation process [5,6]. The application of serious games for health covers a wide range of domains, such as training for behavioral change [7], cognitive exercises [8], the treatment of perceptual disorders [9], or physiotherapeutic exercising (eg, for pain [10] or multiple sclerosis [11,12]). The concept of gamification is an attempt to enrich a context, for example therapeutic exercising, with elements and principles used in game design [5,13]. The main target here is to positively influence the player's attitude, enjoyment, and perceived usefulness toward the game [14]. Gamification can also contribute to improving personal health behavior [15].

The use of video games allows for the creation of exciting adventures for patients who are experiencing certain limitations due to age, illness, or disabilities and can significantly improve their mood [16]. The highly immersive experience that can be generated by the application of virtual reality (VR) technology promises to increase the positive effects on the rehabilitation process even further. The term *virtual reality* in the context of rehabilitation is often used to describe any type of computer-based system, regardless of the level of immersion. Strictly speaking, however, VR refers to a system in which the viewer is surrounded by a computer-generated 3D environment and can move around in this artificial world in real time, view it from different angles, and interact with it [17]. The cost of such immersive systems dropped dramatically after 2013, for example, a 90° field-of-view head-mounted display (HMD) was US $35,000 in 2013 and US $600 in 2016, thus enabling affordable VR hand therapy [18].

Serious Games for Health Regarding Hand Rehabilitation

Input systems for the real-time capture of the patient's hand and finger movements presented in the literature range from haptic devices, such as joysticks [19], robots that allow the fingers to be moved in a targeted manner [20], and data gloves [21,22], to wearable inertial tracking devices [23] and optical tracking systems with either externally placed cameras, such as the Nintendo Wii [24], or low-cost, camera-based tracking systems (eg, the Leap Motion controller that can be used stationary in front of a screen [25,26] or mounted onto a VR HMD). An alternative built-in-one setup is provided by the Meta (formerly Oculus) Quest 2 HMD [12,27]. Such markerless optical tracking generally enables a very simple setup and is also especially beneficial for patients with severely injured skin, burns, or allodynia [18,28].

Many VR and non-VR applications designed for arm and hand rehabilitation can be found in the literature, for example, for the purpose of grasping exercises after-stroke rehabilitation [21] or dexterity training for multiple sclerosis [12]. For practicing the hand and fingers in particular, several examples are given for rehabilitative tasks and activities to be performed in VR, such as playing a virtual piano, catching butterflies, picking flower petals, or solving puzzles [29,30]. Furthermore, assessment-like tasks can be found in VR, such as stacking cylinders into a pegboard or stacking cubes [31,32]. Most of these examples lack a concept that motivates the patient to stick with the game for a longer period but rather rely on the effects of technological novelty and already existing intrinsic motivation. Some tasks provide concepts, such as point systems, eventually combined with playtime and connected to a leaderboard. These rather competitive game elements influence mainly extrinsic motivation and have little effect on intrinsic motivation [33].

Creating Motivational Serious Games for Health

Various types of players exist, and they differ in the degree to which they can be motivated by intrinsic or extrinsic motivation [34]. Although both are vital for engagement, games often focus on extrinsic motivators, such as rewards, achievements, or points, which can be harmful to intrinsic motivation [35]. Intrinsic motivation, by contrast, can be supported by self-initiation and choice [36]. Concepts from self-determination theory, such as competence, relatedness, and autonomy, can help create designs that provide sustaining engagement [37]. Game-based approaches related to self-determination theory can also be drawn from behavior change technology [38,39]. Other key factors in intrinsic motivation are informational feedback and clear game goals, which serve as proof of effectiveness for the patient and can also contribute to extending health beneficial behavior beyond the context of the game [40,41]. Work on gamification discusses the roles of intrinsic and extrinsic motivation, as both are important and not sufficiently studied empirically [33,42].

Objectives

The primary objective of this study was to iteratively design and evaluate a serious game for the rehabilitation of hand and finger function in a patient-centered approach. In contrast to hand rehabilitation games presented in the literature, StableHandVR (BG Klinik Tübingen) had a stronger focus on different motivational factors to promote sustained user engagement for a variety of player types. Similarly, the game was designed to be feasible even for patients with severely limited hand function. The secondary objective was to compare the motivational effects of the rehabilitation game across the design iterations and a control group.

Methods

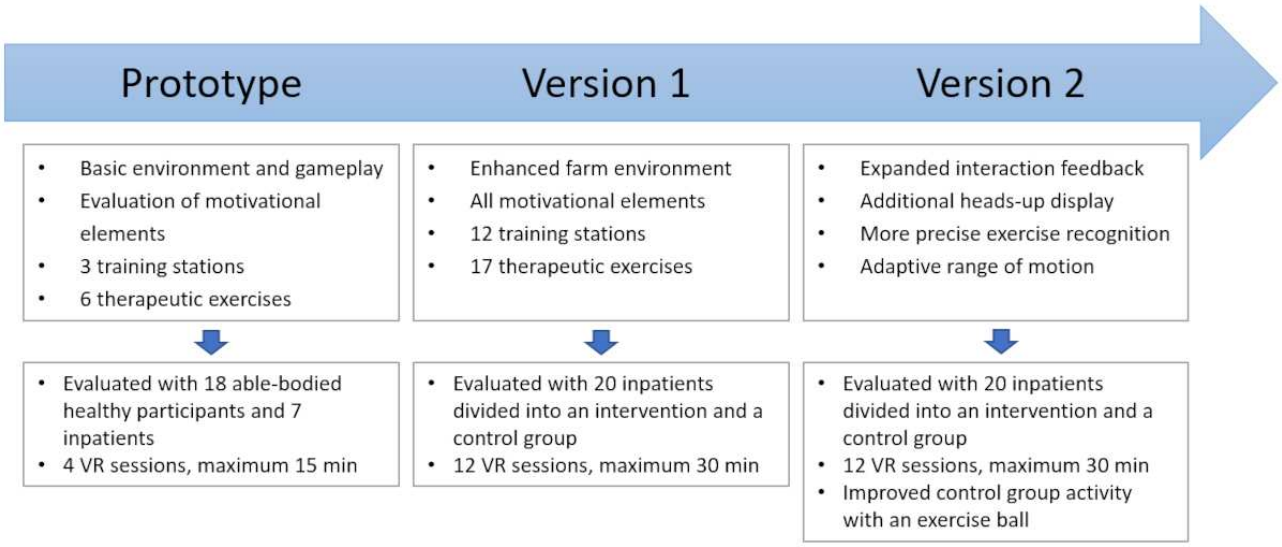
Ethical Considerations

Participant recruitment for the study was conducted in compliance with the Declaration of Helsinki and followed the ethical guidelines by the University of Tübingen, Germany. This study was also approved by the ethics committee of the University Clinic of Tübingen (470/2019B02). Before the initiation of the study, informed consent was obtained from all participants. All data used for this study was anonymized. No compensation was provided to the participants.

Study Design

This study presents the iterative design and development process of the serious game StableHandVR in 3 steps. First, a prototype was created, which provided the core game mechanics and was tested for usability and feasibility. In total, 4 game elements to maintain motivation were designed and evaluated; additional user feedback was collected. On the basis of this preliminary investigation, version 1 of the game was developed expanding the playable content to 3 weeks of training. An intervention group played the game, while a control group watched 360° videos in VR for 12 days during inpatient rehabilitation to evaluate motivational effects. Subsequently, based on the repeatedly gathered feedback and user observation, version 2 was developed and evaluated with the control group's activity being expanded to the use of a training ball to exercise the injured hand while watching the VR videos. Figure 1 presents an overview of the 3 development stages and their evaluation.

Figure 1. StableHandVR underwent 3 successive iterations of development and evaluation. VR: virtual reality.



Apparatus and Setup

All versions of the game were developed in Unity (version 2021, Unity Technologies) for the Meta Quest 2 HMD, running as stand-alone application. The game relied primarily on the use of the inbuilt optical finger and hand tracking feature of the Meta Quest 2; no controllers were required. A physiotherapist could optionally supervise by streaming the visual contents of the HMD onto an Android tablet. The study was conducted in treatment rooms at the hospital with an exercise area of approximately 2×3 meters.

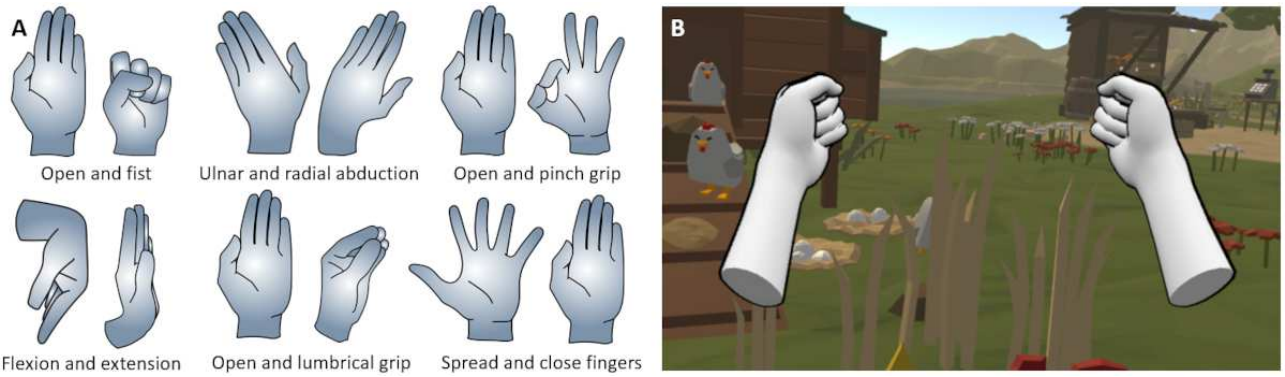
Basic Game Design

StableHandVR aimed to transfer traditional physiotherapy hand and finger exercises into an immersive and motivating virtual world. The inspiration for placing StableHandVR in a natural environment was derived from a study conducted in the 1980s on patients undergoing postoperative recovery [43]. An early feasibility study coined the setting of the game to be a farm environment that provided several training stations to perform exercises [27]. Each station of StableHandVR included a specific task (eg, feeding and milking the cows, preparing a meal, or repairing a tractor), and its completion was divided into 6 exercises, each to be repeated 10 times. Therefore, 60 exercise repetitions had to be performed at each station, and the station's environment would adapt with each repetition, according to the task at hand.

Therapeutic Exercises

The exercises integrated into the serious game were selected by a peer group of physiotherapists and are based on conventional hand mobility therapy [4]. They involved hand and finger movements, wrist movements, and forearm rotations. The prototype included a set of 6 basic exercises, such as closing the hand into a fist or gripping for holding a book (Figure 2).

Figure 2. (A) Overview of the 6 exercises that were used in the prototype. (B) Preview hands as seen in version 2 demonstrated each exercise to the user.



In version 1, the number of exercises was expanded to a total of 17 different movements (a complete list is presented in Multimedia Appendix 1). Throughout the game, the difficulty of the exercises progressively increased. This was achieved by incorporating compound movements, such as simultaneously closing the hand into a fist while pronating the wrist. Moreover, each movement provided the option to be performed with both hands moving in synchrony or in opposite directions, thus adding a further level of complexity and skill requirement to the gameplay.

Performing the exercises neither involved direct interaction with the environment, such as plucking flower petals with the fingertips [44], nor a direct transfer of the patient's hand movements to control the environment [45]. Instead, the environment would adapt automatically at each successful repetition of the exercise, according to the respective task of the station. This design decision was made to ensure good optical tracking of the hands by always being positioned to be clearly visible to the cameras. Furthermore, the original exercise should not be falsified or complicated by being combined with a virtual interaction. Moreover, this design allowed a dynamic composition of exercises for each station on each training day, adjustable for every patient.

In the prototype, preview hands were introduced that would appear in front of the player to demonstrate and clarify the requested hand movements at the beginning of each exercise. The preview hands disappeared after 2 complete repetitions. In version 2, the 3D hand model was expanded by a forearm to provide a more comprehensive visualization of the exercises containing a rotation of the wrist. In addition, instead of dark gray hands, the color was changed to a lighter gray, and the outlines of the hands were highlighted to enhance visibility (Figure 2).

Exercise Tracking and Dynamic Range Adjustment

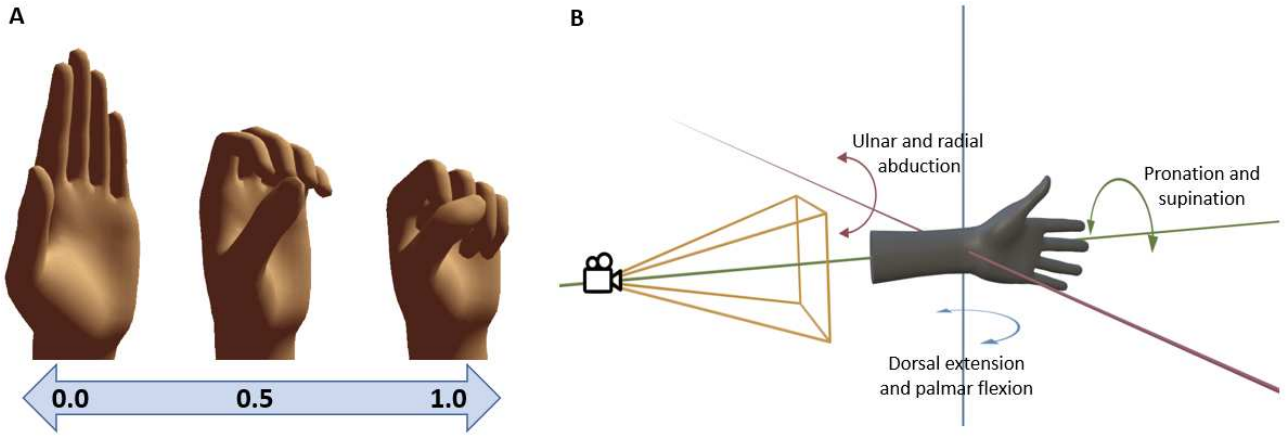
For the prototype, a dedicated component was developed to define and track exercise movements. This component used the hand position model supplied by the Meta Quest software development toolkit. In detail, it made use of the flexion angles of the finger joints within the provided hierarchical bone model to store and reproduce hand positions. By using the HMD, it was then possible to record various hand positions, such as an open hand or a closed fist, and subsequently use these stored positions to define exercise movements by specifying a respective start and end position as well as optional middle positions.

Due to the absence of a forearm in the tracking model of the Quest software development toolkit, the direct extraction of wrist rotation angles was not available. To compensate for this limitation, a reference coordinate system was used in replacement of a forearm bone to determine the rotation of the wrist. This coordinate system had its origin at the player's wrist and was spanned by the vertical axis of the VR environment and a forward axis based on the player's view direction and the forward direction of the hands, leveled within the VR environment by setting its vertical component to 0 (Figure 3). To accurately measure wrist rotation, it was necessary for the player to keep their arms bent forward during the exercise.

In addition to the interface for defining hand and finger exercises, the component was also able to track their execution. Therefore, the players' hand positions were compared to the specified exercise and expressed as a floating-point number within the interval (ie, 0,1). In this representation, 0 denoted the start position, and 1 indicated the end position. If the hand position deviated from the movement, the position was represented as –1.

For each exercise that was newly introduced, the game initially measured the range of motion (ROM) achieved by the player as represented within (0-1). This range was subsequently used to set a minimum target for the player to be exceeded when exercising. In version 2, an adaptive approach was implemented, where the target ROM was recalculated daily, based on the average ROM achieved in the preceding days. The tracking accuracy was also enhanced in version 2 by adding an additional middle position (Figure 3) to all exercise definitions, thus providing a more precise mapping of the player's ROM and adjustment to their skill.

Figure 3. (A) For each exercise movement, a start and end position were defined to determine the position of the hands within the interval (0,1) during exercising. In the second version, additionally a middle position was defined for more accurate measurement. (B) As Meta Quest 2 does not provide wrist tracking, its rotation had to be determined using a reference coordinate system. This coordinate system had its origin at the player's wrist and was spanned by the vertical axis (blue) and the leveled view direction (green). The third axis (red) was defined as perpendicular to the plane spanned by the first 2. This required the forearms to be held approximately along the view direction while exercising.



Interaction Design

Outside of the exercises, the player also used their hands to interact with the game (Figure 4). In the prototype, a teleportation system was created that enabled the player to switch between stations through predefined teleport points by pointing at them. In version 1, a waypoint network was established to allow the player to explore the farm environment also beyond the stations. Starting from version 1, the player was accompanied by a dog character that would provide guidance when touched. The dog's advice was displayed as text within a speech bubble. Nonplayable characters (NPCs) would respond to the player in a similar manner. In version 2, several improvements were implemented regarding the interaction. The teleport system was enhanced by introducing a navigation arrow with the purpose of guiding the player toward the next task. The touch interactions with the dog as well as with NPCs were improved by providing audiovisual feedback. All stations were fully supplemented with audio feedback during exercising; furthermore, an exercise counter was added that would display the number of remaining repetitions during an exercise.

Figure 4. Examples of in-game interaction: (A) petting the dog, (B) teleporting, (C) interaction with a nonplayable character, and (D) performing exercises at the Fireplace station.

Motivational Game Elements

Overview

In total, 4 game elements were developed to sustain patient motivation over the course of a 3-week treatment. These different elements were designed to cater to both intrinsic and extrinsic motivation, ensuring a wide range of motivational factors. The design prioritized preventing patient frustration resulting from limited hand movement and potential therapy-related discomfort, such as pain. At the same time, the game aimed to provide a challenge to less restricted or more competitive players, ensuring they remain engaged without getting bored. Furthermore, there should be no incentive to perform the exercises sloppily, for example, a time challenge. These motivational elements underwent first evaluation in the prototype and were further refined in versions 1 and 2.

Storytelling

The farm was populated with NPCs, which would provide the player with daily tasks, for example, to gather carrots from the vegetable field (Figure 5). In the prototype, initially only 1 NPC was implemented. However, starting from version 1, the farm was populated with 7 NPCs who assigned the player 2 daily tasks, each involving exercises at specific stations. Once the player completed these daily tasks, they gained access to exercise at all the other unlocked stations.

Figure 5. (A) A nonplayable character providing a daily task for the player. (B) The assessment station as seen in version 2 gave an overview of the player's progress. (C) Traffic Light Hands indicate that the movements were performed well. Yellow or green color indicated that the player had reached or exceeded their personal limit. As in version 2, this limit was adjusted daily according to their previous performance. (D) From version 1, the farm contained 12 stations that were unlocked over the course of the game.

Unlocking Rewards

Over the course of the game, the player was rewarded with additional exercise stations. In the prototype, the player unlocked a third station over the first 3 days to become playable on the fourth day. Starting from version 1, the player was rewarded with stations on each day after fulfilling their daily tasks, thus subsequently revealing all 12 stations over the course of the game (Figure 5).

Traffic Light Hands

Different hand colors were used to provide immediate feedback on the execution of movements. This was intended to guide the player toward performing terminal and correct movements while encouraging them to push their personal limit. A red hand color indicated that the patient reached their initially measured ROM, and the game recognized this as a successful repetition. As the patient continued to exceed this ROM, the hand color transitioned from red to orange and finally to green. In version 2, this system was adjusted daily based on the patient's ROM (Figure 5).

Scoring

In the prototype, the player received score points while exercising, based on the aforementioned achieved ROM. A highscore board placed in the middle of the farm presented the scores for each exercise. In version 1, the scoring system was omitted, and in version 2, an assessment station was introduced. This station provided players with visual feedback on their ROM progress throughout the training period for each exercise (Figure 5).

Evaluation

Overview

For all evaluations of StableHandVR, in-house patients from the hospital were recruited. These patients were undergoing inpatient rehabilitation because of limited hand function to such an extent that it restricted their professional and everyday activities. An overview of the type of injuries is given in Table 1. The patients took part in the VR sessions as part of their daily therapy schedule. Prerequisites for participation were basic mobility of the hand (no paralysis or total stiffness); limited hand function; no severe pain at rest (≥9 on a scale of 0-10); and the hand had to be free of stabilizing structures, such as splints, casts, or Kirschner wires. Inclusion criterion for all participants was a minimum age of 18 years.

Table 1. An overview of the injuries of the inpatients that were recruited for the evaluation of the prototype (n=7), version 1 (n=20), and version 2 (n=20).

Type of injury	Prototype, n (%)	Version 1, n (%)	Version 2, n (%)
Fractures in the wrist and hand area	3 (43)	11 (55)	6 (30)
Crush injuries or soft tissue injuries in the hand area	1 (14)	2 (10)	3 (15)
Tendon injuries in the area of the hand	0 (0)	2 (10)	1 (5)
Dislocations or ligament injuries in the area of the hand	1 (14)	1 (5)	1 (5)
Combination of the above points	2 (28)	4 (20)	9 (45)

Evaluation of the Prototype

The evaluation of the prototype involved 1 group of 25 participants consisting of 18 (72%) able-bodied individuals and 7 (28%) inpatients from the hospital (women: n=14, 56%; men: n=11, 25%. The age of the participants ranged from 18 to 56 years, with a mean age of 30.68 (SD 13.3) years. Among the 25 participants, 9 (36%) had prior experience with VR.

Each participant underwent 4 VR sessions conducted over 4 consecutive weekdays, with each session limited to 15 minutes. During each session, participants completed 1 exercise station and had the option to voluntarily complete a second one. In addition, only 1 of the 4 possible motivational game elements (Storytelling, Unlocking Rewards, Traffic Light Hands, and Scoring) was active during each of the sessions. In total, 3 motivational elements were evaluated in a randomized order over the first 3 sessions. In the fourth session, the player was consistently rewarded with access to a third exercise station, thus representing the fourth element, Unlocking Rewards.

After each session, participants rated their experience using 3 scales from the Intrinsic Motivation Inventory (IMI) questionnaire [46], specifically *interest and enjoyment*,*effort* and *pressure* on a 7-point Likert scale. In addition, participants were interviewed to gather their feedback on the game, suggestions for improvements, and ideas for additional content. The open-ended answers were evaluated based on the grounded theory [47] and thematic analysis [48].

Evaluation of Version 1

In total, 20 inpatients (women: n=6, 30%; men: n=14, 70%) from the hospital were equally assigned to either intervention or control group. The age ranged from 24 to 70 years, with a mean age of 48.8 (SD 12.3) years. Of the 20 inpatients, 8 (40%) had prior experience with VR.

During their 3-week inpatient rehabilitation program, both groups completed 12 VR sessions on consecutive weekdays in addition to their regular rehabilitation therapy. Each VR session was limited to 30 minutes and was supervised by a physiotherapist. In the intervention group, patients played the VR game and completed 2 mandatory tasks in each session. Additional training stations that were already unlocked could be voluntarily explored. New exercises were introduced every fourth day. In the control group, patients used the VR headset to watch a 360° video during each session, with durations ranging from 10 to 15 minutes. Following the final session, both groups were surveyed using the *interest and enjoyment*, *effort*, *usefulness*, and *pressure* subscales of the IMI questionnaire. The intervention group also evaluated the VR game using the Mobile Application Rating Scale (MARS) questionnaire [49], with the scales *engagement*, *functionality*, *aesthetics* and *impact on knowledge and attitudes* rated on a 5-point Likert scale, and was interviewed to gather feedback on the game. For further analysis of the user behavior, the game automatically recorded all user interactions in a time log.

Evaluation of Version 2

In total, 20 inpatients from the hospital were equally assigned to either the intervention or control group. One patient dropped out after the second session in the intervention group and another after the third session in the control group. The intervention group dropout was due to a dislike for the game, while the control group dropout was due to a transfer to another hospital. Both dropouts were replaced by 2 additional patients. All following analyses refer to the 18 remaining original patients and the 2 replacements.

The age of the final 20 patients (women: n=10, 50%; men: n=10, 50%) ranged from 22 to 61 years, with a mean age of 38.1 (SD 12.9) years; Of the 20 inpatients, 5 (25%) had prior experience with VR. The evaluation of version 2 followed a similar approach as version 1, with 2 modifications to the test protocol. First, the activity of the control group was extended by incorporating a crumple ball exercise for patients to engage their injured hand while watching the VR content. This addition aimed to provide an unspecific exercise for the injured hand. Second, patients in the intervention group had to rate the game using the System Usability Scale (SUS) [50] on a 5-point Likert

scale after the last session. This measure was introduced to gather validated feedback on the usability of the game.

Data Analysis

All statistical analyses were performed with MATLAB for Windows (version R2021a; MathWorks) with a significance level of α=.05. To assess demographic effects, patients from the evaluations of versions 1 and 2 were consolidated and categorized into 5 age groups (<30, 30-39, 40-49, 50-59, and >60 years), into a group of women or men, and a VR-experienced versus no VR-experience group. All data gathered from the automatic tracking were tested for normal distribution using the Kolmogorov-Smirnov test. Due to the small sample sizes, nonparametric tests were used for all analyses. For multiple pair-wise comparisons, the Kruskal-Wallis test was used with the *P* level adjusted by Bonferroni correction. For single pair-wise comparisons, the Wilcoxon rank sum test was used. Demographic data, temporal data, and variables gathered from questionnaires were represented as mean (SD); the number of stations per day and the duration of exercise repetitions, gathered from the automatically tracked in-game data were represented as mean (SE).

Results

Prototype Results

All 25 participants completed the 4 VR sessions, and none of them reported vertigo or discomfort at any point. Over the course of the 4 sessions, all participants learned to operate the game without assistance. The mean VR playtime for each session decreased from 14.5 (SD 0.65) minutes for the first session to 10.6 (SD 0.82) minutes for the last session. All participants were able to perform the 6 exercises in a way that the game could recognize them. The mean duration needed to perform 1 repetition of an exercise decreased from the first to the fourth session from 7.1 (SD 0.35) to 6 (SD 0.38) seconds for the patients and from 5.6 (SD 0.26) to 4.7 (SD 0.24) seconds for the able-bodied participants.

The evaluation of the game elements with the IMI questionnaire resulted in high scores for all 4 elements on the 2 subscales *interest and enjoyment* and *effort* and low scores on the *pressure* subscale (Multimedia Appendix 2). There were neither substantial differences between the elements nor over the course of the 4 days. When asked about their most favored motivational element in the interviews, the Traffic Light Hands and Unlocking Rewards both were mentioned most frequently (8 mentions), followed by Storytelling (6 mentions) and Scoring (3 mentions), which lacked significance for many participants, as they always achieved the full ROM and therefore the maximum number of points.

The overall feedback gathered from the interviews was highly positive; the farm setting displayed in the game was widely regarded as pleasant and appealing (10 mentions). The direct feedback of the Traffic Light Hands (6 mentions), the interactive aspects of the station environments that would adapt during the execution of the exercises (5 mentions), the animals on the farm including the dog companion (4 mentions), and the general idea of gamifying a rather boring rehabilitation activity (4 mentions) were also positively mentioned. The least favored experiences were the recognition of the exercises (4 mentions), and the low number of exercise stations (4 mentions). The most mentioned suggestions for improvements were more variety in general (6 mentions), more exercise stations (4 mentions), enhanced storytelling (2 mentions), more variety in exercise movements (2 mentions), and a larger farm area to explore (2 mentions). When asked about suggestions for additional content, many suggestions were made for additional training stations related to farm work, mostly regarding animals (7 mentions) but also regarding the farm infrastructure (4 mentions), such as the farmhouse or the tractor, and activities regarding the lake (3 mentions).

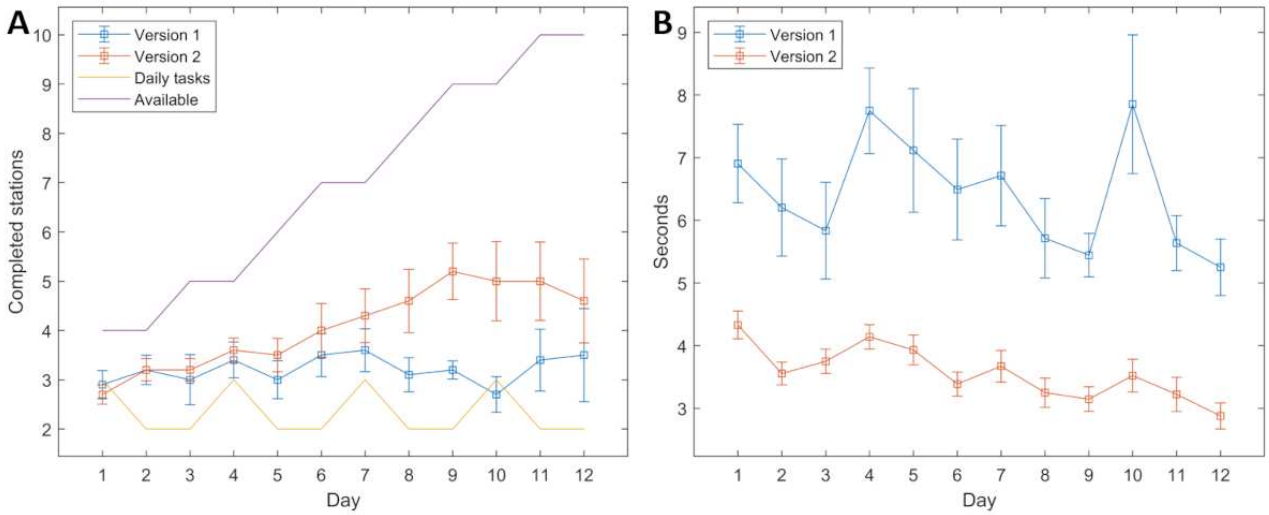
Version 1 Results

All 20 patients in both groups completed the 12 VR sessions; no patient reported any experience of discomfort or motion sickness. The mean VR playtime of the intervention group was 25.3 (SD 5.9) minutes on the first day and 26.4 (SD 10.6) minutes on the last day, with a mean playtime of 22.8 (SD 7.1) minutes over all days. The mean number of stations played per day was higher than the mandatory amount specified by the daily tasks on all days except for the 1st and the 10th day (Figure 6). Due to their limited hand function, some patients had problems performing the exercises such that they were recognized by the game, especially on the 10th day when the last set of exercises was introduced. The mean duration of the execution of 1 exercise repetition increased strongly on the days when new exercises were introduced (Figure 6) but decreased over the course of the 12 days from 6.9 (SE 0.62) seconds to 5.3 (SE 0.45) seconds.

The MARS rating resulted in high scores for all subscales: *engagement* (mean 4.18, SD 0.42), *functionality* (mean 4.17, SD 0.47), *aesthetics* (mean 4.2, SD 0.48), and *impact on knowledge and attitudes* (mean 4.7, SD 0.35; Multimedia Appendix 3). All IMI subscale scores were slightly higher in the intervention group than in the control group (Multimedia Appendix 4); significant differences were found for the subscales *effort* (P<.001) and *usefulness* (P=.02).

The user observation indicated that most patients could navigate the game independently without assistance after the initial 2 days, except when new exercises were introduced. The visual and textual instructions provided by the preview hands and the dog companion were occasionally unclear, requiring clarification from the assisting physical therapist. Some patients had difficulties with orienting themselves on the farm, especially on the first days. At the training stations, it was not always clear for some patients where the action was taking place to signify task completion. Patients mentioned difficulties regarding exercise counting, and they expressed the need for a visible counter and more auditory feedback at the stations to signal when a repetition was completed.

Figure 6. (A) The mean number and SE of completed stations in version 1 and version 2 as well as the minimum amount demanded by the daily tasks and the maximum possible number of stations for each day. (B) The mean duration and SE that were required to execute 1 repetition of 1 exercise in version 1 and version 2. New exercises were introduced on days 1, 4, 7, and 10.



Both groups reported perceiving the VR sessions as a vacation from their inpatient stay. They were able to momentarily forget about their injuries, felt being transported to another place, and experienced a sense of tranquility. The feedback from the intervention group regarding their game experience again was highly positive. The Traffic Light Hands were frequently mentioned for motivating patients to extend their limits toward terminal movements (6 mentions) and providing feedback on correct exercises (4 mentions); the immersive scenario, which made patients lose track of time during practice (6 mentions), and the virtual representation of their hand, which made them forget their injury (4 mentions), were also mentioned frequently. Some participants expressed their wish for an option to observe their progress, for example, as a score system that was not present in version 1.

Version 2 Results

A total of 20 patients completed the 12 VR sessions, of whom 19 (95%) did not report any discomfort or motion sickness and 1 (5%) answered with "don't know." The mean VR playtime of the intervention group was 20.3 (SD 5.9) minutes on the first day and 16.7 (SD 8.5) minutes on the last day, with an overall mean of 20.9 (SD 8.9) minutes on all days. The mean number of stations played was higher than in version 1 after the second day (Figure 6), and the overall mean of stations played was significantly higher (P=.008). All patients were able to perform the exercises in a way that was recognized by the game. The mean duration for performing 1 exercise repetition decreased from 4.6 (SE 0.24) seconds on the first day to 2.6 (SE 0.23) seconds on the last day. On the days with new movements being introduced, the increases were not as pronounced as in version 1 (Figure 6). The overall mean duration for performing 1 exercise repetition was significantly lower than that in version 1 (P<.001).

Compared to version 1, the MARS rating resulted in slightly higher scores for the subscales *engagement* (mean 4.24, SD 0.71) and *functionality* (mean 4.28, SD 0.42) and in slightly lower scores for the subscales *aesthetics* (mean 4.0, SD 0.63) and *impact on knowledge and attitudes* (mean 4.14, SD 0.73; Multimedia Appendix 3). The SUS rating resulted in a mean score of 86.9 (SD 3.3), which ranges in the fourth quartile and represents excellent acceptability. The scores of the IMI subscales were higher for the intervention group (Multimedia Appendix 4) than for the control group, with significant differences for the subscale *effort* (P=.02).

Similar to version 1, the user observation indicated that patients were able to operate the game without assistance after the first 2 days but required some assistance in learning new exercise movements. Orientation on the farm and at the stations was comprehensible for all patients, and performing the exercises caused the patients less difficulty than in version 1. Both groups reported the relaxing effect of the VR experience, and the most mentioned categories regarding the overall feedback from the interviews were similar to version 1: the Traffic Light Hands (5 mentions), the immersive game experience (5 mentions), and the virtual representation of the hands (3 mentions). Furthermore, the execution of the exercises was mostly described as working well (5 mentions). The newly designed Scoring element, providing a progress overview of the ROM at the assessment station, experienced the same issues as in the prototype, namely, always showing the possible maximum of points for the most exercises. Therefore, it was described as not very meaningful and was predominantly not used. Suggestions were made to provide other scenarios, such as a dungeon- or sci-fi–themed environment. Patients also raised the wish for a more personalized experience, and suggestions were made, for example, custom paint for the farmhouse or customizable virtual hands. Finally, recommendations for activities regarding the lake were mentioned again, such as fishing or riding a boat.

Demographic Effects

Regarding age, the 40- to 49-year age group showed the lowest number of completed stations among all age groups as well as the lowest IMI scores for *interest and enjoyment*, *effort*, and *usefulness*, while high scores for *pressure* were reported. The 30- to 39-year age group completed the most stations, and the <30-year age group reported the highest IMI scores for *interest and enjoyment*, *effort,* and *usefulness* and the lowest *pressure*

score. Men played more stations than women patients and accordingly had higher IMI scores for *interest and enjoyment*, *effort*, and *usefulness,* with a lower *pressure* score. Patients with no prior VR experience completed more stations per day than patients with prior VR experience. However, the latter rated higher IMI scores for *interest*, *effor*t, and *usefulness* but also a higher score for the *pressure* scale. The complete list of values is presented in Table 2.

Table 2. Number of stations completed per day and Intrinsic Motivation Inventory scores (1-7 scale)[a].

Demographic group	Stations per day, mean (SE)	Interest and Enjoyment, mean (SD)	Effort, mean (SD)	Pressure, mean (SD)	Usefulness, mean (SD)
Gender					
Men (n=11)	3.89 (0.6)	6.4 (0.6)	6.1 (1.0)	2.0 (0.6)	6.5 (0.6)
Women (n=9)	3.34 (0.5)	6.3 (1.1)	6.0 (1.0)	1.9 (0.7)	6.3 (1.2)
VR[b] Experience					
Prior VR experience (n=4)	3.04 (0.5)	6.4 (0.9)	6.1 (0.6)	2.2 (0.7)	6.5 (0.5)
No prior VR experience (n=16)	3.79 (0.6)	6.3 (0.8)	6.0 (1.0)	1.9 (0.7)	6.4 (0.9)
Age group (y)					
<30 (n=2)	3.58 (0.3)	6.6 (0.6)	7.0 (0)	1.5 (0.7)	6.9 (0.2)
30-39 (n=4)	4.98 (1.5)	6.0 (0.6)	5.8 (0.7)	1.7 (0.4)	6.3 (0.6)
40-49 (n=3)	2.97 (0.9)	5.9 (2.0)	5.7 (1.5)	2.1 (0.7)	5.5 (2.1)
50-59 (n=8)	3.08 (0.3)	6.6 (0.5)	6.0 (1.0)	2.1 (0.8)	6.8 (0.2)
>60 (n=3)	4.05 (1.1)	6.3 (0.3)	6.3 (0.7)	2.0 (0.3)	6.1 (0.4)

[a]The data were consolidated from version 1 (n=10) and version 2 (n=10) and categorized by demographic groups.

[b]VR: virtual reality.

Discussion

Principal Findings

In this study, we iteratively developed a serious health game for hand and finger rehabilitation with the deliberate goal of contributing to the long-term engagement of patients. The game was developed for the Meta Quest 2 because this HMD with built-in finger tracking allowed for a very simple and fast setup. A second reason for this decision was the finger tracking of the device, which produced better results than the Leap Motion or UltraLeap controllers when performing certain finger positions that were considered important, for example, the thumb touching ≥1 long fingers.

The iterative development and evaluation steps ensured a patient-centered design process by user observation and feedback through semistructured interviews. In general, participants reported a high level of immersion that allowed them to temporarily escape from their inpatient setting into another world. This was reported by both the intervention group and control groups and impressively confirms the potential of VR as described in the literature [18,51]. The setting of the farm environment and the display of nature were overall received very positively, a design decision that was also inspired by literature [43]. However, in the original intervention group of version 2, one patient quit after the second session because they did not like the game in general. In terms of engagement, we observed the entire spectrum from patients who tended to be underchallenged to patients well within their physical and cognitive limitations. We attribute these differences not only to varying levels of hand function but also to contrasting user preferences (eg, purpose vs mastery) [34], possibly coined by the practice of playing video games.

We expected a decrease in motivation related to the higher age of the participants and thus less familiarity with video games [52]. The familiarity was reflected by the IMI subscale *pressure*, which was clearly lowered for the <30- and 30- to 39-year age groups. However, while the 40- to 49-year and 50- to 59-year age groups completed the fewest stations per day, the >60-year age group reached the second highest value, only surpassed by the 30- to 39-year age group and before the <30-year age group. Differences in the number of stations completed between genders are smaller than between VR and no VR experience. The other IMI scales *interest*, *effort*, and *usability* show only minor deviations for all demographic groups. From these findings, it could be concluded that while age, gender, or the effect of technological novelty due to using VR for the first time might affect the overall motivation, these demographic effects did not harm the intrinsic motivation of the patients.

Compared to their control groups, higher IMI scores were measured for both intervention groups, and significant differences were found for the subscales *effort* in version 1 and version 2 and *usefulness* in version 1. It should be mentioned that, surprisingly the control groups were also very motivated to watch the videos, which again demonstrates the potential of using VR in the context of rehabilitation. However, we assume that in an unsupervised setting, the motivation in the control

groups would have decreased more compared to the intervention groups [2] because the game, as used in our study, still represented a form of supervision. The assurance of performing the therapeutic exercises correctly may have been a key factor for the significantly higher IMI subscale *usefulness* of the intervention group, as scored in version 1 [41]. According to the MARS questionnaire, awareness for conscious health behavior could be raised for the intervention groups, which is linked to perceived attitude, enjoyment, and especially usefulness [14,15].

To engage a wide range of player types, 4 motivational game elements offering different motivational factors were developed. The element Storytelling should provide tasks and a context, Unlocking Rewards should offer new incentives for discovery, the Traffic Light Hands would provide direct feedback, and the Score would provide long-term feedback [34]. Among these 4, the first 3 elements can be considered rather successful, as they scored high on the IMI questionnaire and the subscales *effort* and partially also *usability* were significantly higher than in the control groups. In particular, the Traffic Light Hands received positive feedback in the interviews. This direct biofeedback, which is a critical factor for intrinsic motivation [41,53], not only encouraged patients to perform terminal movements but also gave them confidence to exercise correctly.

In contrast, the Scoring element already proved to be unsuccessful in the prototype stage because it lacked meaningfulness in terms of showing the patient's ROM improvement. This was mainly caused by the fact that many players were able to perform most exercises with full range from the beginning. Due to the ambiguity, the element was discontinued in version 1 to avoid negative feedback and discouragement. Due to the frequent demand to visually represent the progression of ROM, the element was reintroduced in version 2 with a different design, which did not work properly for the same reasons. Therefore, the resulting lack of competitive motivational elements might be the main reason why the game was not challenging enough for some patients [34]. Furthermore, the lack of visualization of the therapy progress deprived patients of evidence of efficacy, which is also a key motivating factor for health games [41].

The comparison of versions 1 and version 2 shows a significantly higher number of stations played per day, from which it can be concluded that the overall motivation in version 2 was higher. Besides the improved interaction feedback, also reflected by a high SUS score, the most obvious improvement was the tracking accuracy of the therapeutic exercises, which can clearly be seen by the mean time that was required for a single exercise repetition being reduced by almost half. This circumstance may be mainly responsible for the fact that more stations were played. However, this interpretation must also consider that the mean age of the patients in version 2 was 10 years lower than in version 1. In both versions, a similar amount of time was spent in the game, on average approximately 22 minutes. As there were no significant differences in the IMI scores between version 1 and version 2, we conclude that the improvements did not affect the intrinsic motivation, which was already high in version 1.

Limitations

Patients attended the VR sessions after their daily rehabilitation routine and may have been exhausted, which could potentially affect their motivation negatively. By contrast, we can assume that by being part of their daily routine, the supervised participation in VR sessions, although voluntary, was accompanied by stronger motivation than if it had been unsupervised [2]. The large variation in the degree of injury and impairment between individual patients may have influenced the outcome of measured and observed motivation. A larger sample size would better compensate for this effect.

Due to the short evaluation time of only 12 days, it was only partially possible to measure the long-term course of motivation.

Outlook and Future Challenges

While we acknowledge the challenges in making the game equally appealing and challenging for all patients, our approach of incorporating a mix of extrinsic and intrinsic motivational elements was generally successful. By individually adjusting the composition of the movements, the challenge level of the game could be easily increased for underachieving players. It has also become apparent that there is a great need for a working score system or at least a therapy progress indicator. To build up compliance and adherence among patients, this proof of effectiveness is a key factor and needs to be improved. Due to the missing forearm tracking and inaccuracies in detecting individual phalanges [54], especially within an unusual finger or hand position, the correct execution of the patient's movements and the assessment of their ROM was limited. We expect this feature to improve over the next few years, enabling us to overcome these limitations. In the meantime, a point system could be implemented that is simply based on the number of exercises already completed.

In the context of the general shortage of therapists, it would be beneficial to use StableHandVR in an unsupervised setting, for example, at home for several weeks, following the inpatient stay. The evaluation of StableHandVR in an unsupervised setting for an extended period would also be an exciting next step from the perspective of this study. In such a setting, we see the biggest challenge for our game, both in terms of user engagement and in substituting the physical therapist, whose assistance is currently still required for correctly learning new exercises.

Finally, StableHandVR could easily be transferred into other domains where hand and finger exercises are required, such as in stroke rehabilitation [21] or multiple sclerosis [12]. As StableHandVR allows for the simple creation of additional therapeutic exercise movements, it could be extended within a short time for other motor exercises. Furthermore, we think that the promising use of different motivational elements as in StableHandVR would also be beneficial for a variety of other applications that use gamification in a therapeutic context to achieve user engagement.

Conclusions

This study showcased a VR game designed for hand and finger rehabilitation exercises. The iterative development process allowed user feedback to be incorporated into further

development. The game was well received, offering an engaging environment and various elements that effectively motivated the users. Despite impaired hand function, the tracking of therapeutic movements proved to be reliable in operating the game. The high SUS score confirms the ease of use of the game, even for patients with physical limitations. With ongoing technical advancements in optical finger tracking, we anticipate even greater accuracy in the future, paving the way for automated medical assessments and telerehabilitation scenarios. This creates the potential for StableHandVR to become an unsupervised yet engaging VR health game for postrehabilitation home use.

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Authors' Contributions

MB contributed to the game design, implemented all versions, contributed to the evaluation, analyzed the data, and wrote the manuscript. JM contributed to the game design, contributed to the evaluation, and revised the manuscript. TG contributed to the game design, performed the experiments, collected the data, and revised the manuscript. FK contributed to the game design, contributed to the interpretation of the results, and revised the manuscript. AD and JK contributed to the critical revision of the intellectual content and approved the final version. CP contributed to the methodology and the game design, revised the manuscript, and oversaw overall direction and planning. All authors provided critical feedback and helped shape the research, analysis, and manuscript. All authors contributed to the article and approved the submitted version.

Conflicts of Interest

None declared.

Multimedia Appendix 1

Overview of the therapeutic exercises.
[PDF File (Adobe PDF File), 708 KB-Multimedia Appendix 1]

Multimedia Appendix 2

Intrinsic Motivation Inventory (IMI) scores per game element in the prototype. During the prototype evaluation, participants rated their experience for each game element using the IMI questionnaire. Error bars indicate the SD of the mean.
[PNG File , 59 KB-Multimedia Appendix 2]

Multimedia Appendix 3

The mean scores and SD for version 1 and 2 rated by the intervention groups using the Mobile Application Rating Scale questionnaire.
[PNG File , 86 KB-Multimedia Appendix 3]

Multimedia Appendix 4

Mean scores and SD of the evaluated Intrinsic Motivation Inventory scales of the intervention group compared to the control group for version 1 (A) and version 2 (B). Statistically significant at $P<.05$.
[PNG File , 54 KB-Multimedia Appendix 4]

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Abbreviations

HMD: head-mounted display
IMI: Intrinsic Motivation Inventory
MARS: Mobile Application Rating Scale
NPC: nonplayable character
ROM: range of motion
SUS: System Usability Scale
VR: virtual reality

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PhantomAR: gamified mixed reality system for alleviating phantom limb pain in upper limb amputees—design, implementation, and clinical usability evaluation

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Abstract

Background Phantom limb pain (PLP) is a restrictive condition in which patients perceive pain in a limb that is no longer present, greatly reducing their quality of life. Mirror Therapy, wherein patients observe a mirror reflection of their intact limb, has demonstrated efficacy in alleviating PLP. However, its unilateral and seated nature presents limitations. To address these constraints while still reducing PLP, and evaluating the impact of different virtual limb representations (anthropomorphic vs. non-anthropomorphic) on the user's sense of ownership, agency, and embodiment, PhantomAR was developed. Leveraging wearable first-person augmented reality (AR) technology, PhantomAR extends traditional Mirror Therapy by enabling users to move freely and engage in bimanual tasks.

Methods The assistive mixed reality game application PhantomAR was deployed on the Microsoft HoloLens 2 and augmented the user's residual limb by superimposing a virtual arm or tentacle that was controlled via residual muscles on their stump using an EMG electrode array. This setup allowed patients to engage in a first-person perspective and manipulate virtual objects with both the healthy and augmented limbs, free from the confines of a seated position. The study enrolled 10 able-bodied individuals and 8 individuals with unilateral, transradial amputation. All amputees experienced PLP. The usability of the PhantomAR application was evaluated using the System Usability Scale (SUS) and a user-centric survey. Additionally, the Game Experience was assessed on a 5-point Likert questionnaire (GEQ). Participants rated their phantom sensations using the Numerical Rating Scale and McGill Pain Questionnaire before, during, and after interaction with PhantomAR. The embodiment and agency of the virtual superimposed arm were evaluated with an altered Prosthesis Embodiment Scale. The study protocol included two sessions of 30 min each, during which participants experienced PhantomAR.

Results Participants (n = 18) rated PhantomAR highly usable (SUS m = 90.8%, SD = 6.88). Feedback on the Game Experience Questionnaire was overwhelmingly positive, showing high immersion (m = 4.46, SD = 0.08) and positive affect (m = 4.97, SD = 0.05). PLP (n = 8) significantly decreased post-intervention (NRS and McGill Pain Questionnaire, $p < .001$). Skin temperature in the residual limb increased significantly post-intervention ($p < .01$) but did not correlate with PLP ($r = -0.08$, $p = 0.83$). Tentacle overlay yielded mixed ownership but high agency ratings.

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Conclusion PhantomAR leverages mixed reality to significantly reduce Phantom Limb Pain, enhance user engagement, and alter perceptions of ownership and agency of their augmented limb through bi-manual, dynamic, full-body interactions.

Trial registration DRKS00033208 (Jan. 5th 2024)

Keywords Upper limb amputation, Hand amputation, Mirror therapy, Gamification, Phantom limb pain, Prosthesis, Myoelectric control, Mixed reality, Extended reality, Microsoft HoloLens 2

Background

Many upper limb amputees report the sensation of a phantom limb, with some describing not only the presence but also various sensations associated with it. These sensations include proprioception of the phantom limb, awareness of its volume, spatial location, and occasional cramps or spasms [1, 2]. Additionally, an estimated 80% of amputees perceive painful sensations in their missing limb, referred to as Phantom Limb Pain (PLP) [3, 4]. It significantly diminishes their quality of life, causing distress and hindering daily activities, mental well-being, and overall health [3, 5–8]. PLP manifests in diverse ways, with common descriptions including burning, gnawing, lacerating, pressure, and distorted positioning [9–11]. Some patients experience improvement over time, while others may continue to have persistent pain, making it an issue that requires ongoing treatment [12, 13].

Efforts to manage PLP have encompassed both pharmacological and non-pharmacological approaches, but they often fall short of providing complete relief [8, 14–16]. The drawbacks of pharmacological treatments, such as potential side effects like daytime fatigue and personality changes, highlight the need for effective non-pharmacological alternatives. As for these, Mirror Therapy is the predominant treatment modality for Phantom Limb Pain. This therapy involves the placement of a mirror in a sagittal position adjacent to the patient's intact limb, prompting the patient to visualize the reflection as a substitute for the contralateral amputated limb. This technique promotes a perception wherein the brain interprets the amputated limb as intact and mobile, effectively creating a non-painful illusion of the absent limb [17]. The efficacy of Mirror Therapy is largely attributed by neuroplasticity-based hypotheses of PLP to its provision of anthropomorphic visual feedback, which is recognized as a key factor in its therapeutic impact [18–20]. However, during Mirror Therapy, the patient is limited to only unilateral movements which, moreover, take place in a seated position. The patient does not have agency over the residual limb. These restrictive circumstances potentially limit the engagement, sustained motivation and embodiment of the patients, which are believed to be main driving factors of PLP reduction [19, 21–23].

Research has suggested that changes in skin temperature in the residual limb may correlate with the intensity of Phantom Limb Pain. Some studies have reported that increased pain intensity is associated with higher skin temperatures in the residual limb [24], while others have found no significant correlation [25, 26]. However, the amputation stump was almost always invariably colder than the corresponding point of the contralateral side [25, 27, 28]. Skin temperature is regulated by the body's vasomotor response, which adjusts blood flow and consequently, skin temperature through processes like vasodilation and vasoconstriction [29]. Physical activity has been shown to boost circulation to the limbs [29], which could either contribute to pain perception in those with PLP or offer temporary relief by promoting relaxation and reducing muscle tension.

Recent advancements in PLP treatment increasingly leverage digital technologies such as Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR) using devices such as Meta Quest and Microsoft HoloLens to immerse users in virtual settings. In VR-based mirror therapy, the mirror image is substituted with a digital representation of the absent limb which is mirrored to the movements of the healthy limb [30–33]. AR extends this concept by superimposing virtual objects onto real-world views. This includes applications that project an augmented image of an intact limb over the residual limb on a computer screen using a camera and QR code [5, 34–37] or custom AR platforms by augmenting VR headsets with cameras to help alleviate Phantom Limb Pain (PLP) and train myoelectric control [38, 39]. Previous studies using screen-based AR primarily focused on myoelectric prosthesis control and the transferability of tasks from virtual environments to real-world settings, involving pick and place tasks [40] for pattern recognition control [41] or motor skill enhancement [42].

Mixed Reality advances this approach by allowing interactions between virtual and real objects, enhancing realism and engagement and spatial awareness, while first-person views via commercially available see-through glasses, such as the Microsoft HoloLens, Magic Leap or Google glasses, facilitate more accurate interactions and thus embodiment [43–51]. Immersive virtual reality technology is emerging as a successful nonpharmacologic

adjunctive analgesic in reducing acute procedural pain. This is particularly evident in its application during dressing changes and in physical and occupational therapy [21].

In the context of healthcare gamification, research indicates that patient adherence to prescribed home rehabilitation exercises is often suboptimal, attributed to lack of motivation in absence of a supervising therapist [52, 53]. This challenge in motivation and compliance is a recurrent issue in clinical practice [54, 55]. Meta-analyses have highlighted the beneficial role of gamification strategies in enhancing health outcomes [56, 57]. Additionally, various studies have demonstrated the positive impact of gamification on therapy adherence, motivation, skill training, and learning in disease management [58–60]. A systematic review acknowledges the potential benefits of games for health while also underscoring the necessity for further methodologically sound studies in this [61]. Moreover, some researchers stress the importance of involving the target population, such as individuals with amputations, in the design and evaluation process. Observing how these users engage with mixed reality technology provides valuable insights into usability, user experience, and areas that may require adaptation or improvement to better meet their needs [62].

Building upon mirror therapy, PhantomAR offers an immersive mixed reality experience for individuals with transradial amputations. While mirror therapy utilizes visual illusion of a complete limb for pain reduction, PhantomAR extends this concept. It liberates patients from a static position, allowing free exploration and bimanual interaction through a non-mirrored virtual limb. This virtual limb augments the residual limb and operates independently from their unaffected limb. Additionally, PhantomAR incorporates gamified elements to stimulate curiosity and engagement.

This study centered on designing, implementing, and evaluating PhantomAR, particularly focusing on:

- Evaluating the usability of PhantomAR, which allows free movement and bimanual interaction, and its effect on the intensity of PLP: We hypothesized that the intensity of PLP will decrease following the use of the mixed reality system. Additionally, we hypothesize that healthy participants will report high usability and engagement scores when using PhantomAR, with fewer physical challenges affecting their interaction, providing a baseline for system performance.
- Investigating the impact of different virtual limb representations (anthropomorphic vs. non-anthropomorphic) on ownership, agency, and embodiment: We hypothesized that there will be differences in the levels of ownership, agency, and embodiment experienced by able-bodied and amputated participants when interacting with anthropomorphic versus non-anthropomorphic virtual limb representations. However, we do not make a specific directional prediction, as the influence of non-traditional designs, such as a tentacle, remains largely unexplored.
- Exploring the potential relation between skin temperature changes and PLP: We hypothesized that increases in skin temperature will be observed during the use of PhantomAR, potentially correlating with a reduction in PLP. We further hypothesize that the magnitude of temperature changes will differ between the amputee and healthy group cohort.

Methods

Participant recruitment for the study was conducted in compliance with the Declaration of Helsinki and followed the ethical guidelines by the University of Tuebingen, Germany (181/2020BO1). Prior to the initiation of the study, informed consent was obtained from all participants. Participants consisted of a cohort of ten able-bodied individuals (7 males, 3 females, aged 29.6 ± 8.6 years) and eight individuals with unilateral, transradial amputations (8 males, 2 females, aged 45.1 ± 7.8 years). Out of these 8 patients, 5 had already received a prosthesis, however, all stated that they did not use it regularly. All patients experienced medium to high PLP, which either appeared episodically (potentially triggered by activities or stress, with intermittent relief) or constant (mostly without significant periods of relief). 2 patients were taking regular pain medication (Table 1).

The usability of the PhantomAR application on the HoloLens 2 was assessed using the **System Usability Scale** (SUS). The SUS, a 10-item questionnaire using a 5-point Likert scale, is a widely accepted tool for evaluating a range of products, including software applications [63]. In addition, a **user-centric survey** comprising 10 questions was conducted to assess aspects such as immersion, ambience, control, interaction with virtual and real objects, and the comfort of wearing the HoloLens 2.

Participants' motivation in using PhantomAR was evaluated using the **Game Experience Questionnaire (GEQ),** which includes 5 main subscales (positive affect, negative affect, flow, challenge, immersion) and 2 additional subscales for tentacle ownership and tentacle agency, rated on a 5-point Likert scale with 1 meaning "completely disagree" and 5 meaning "completely agree" [64].

Patients were additionally asked to rate their phantom limb pain before, during, and after the interaction using the Numerical Rating Scale (**NRS**). Phantom

Table 1 Demographic data of the patients

Patient ID	Level of amputation	Stump length [% of intact limb]	Amputation side	Dominant hand	PLP Baseline	PLP frequency	Pain medication per day	Received prosthesis	Wears prosthesis	Received MT	MT worked	Age	Gender
1	TR	51%	Right	Right	7	Constant	None	y	n	y	n	45	f
2	TR	37%	Right	Right	4	Constant	None	y	y	y	n	57	m
3	TR	45%	Right	Right	5	Episodic	None	y	n	y	n	45	m
4	TR	47%	Right	right	4	Constant	None	y	y	n	-	37	m
5	TR	28%	right	right	7	Episodic	300mg GP	y	n	y	n	41	f
6	TC	80%	left	Right	5	Episodic	None	n	–	n	–	49	m
7	TR	42%	Left	Right	4	constant	200mg GP, 5 mg Oxyco-done	n	–	n	–	33	m
8	TC	67%	Right	right	5	episodic	None	n	–	n	–	21	m

Stump length has been measured from the lateral epicondyles. MT = Mirror Therapy, GP = Gabapentin, y = yes, n = no

limb and sensation was further assessed by the German version of the Short Form McGill Pain Questionnaire (**SF-MPQ**) [65] during baseline and post-intervention measurements. The McGill Pain Rating Index (**PRI**) is constructed by adding up the scores of 15 pain qualities which are rated on a scale of 0 ("none") to 3 ("severe"). Therefore, the PRI score ranges from 0 to 45.

Skin temperature was measured with a contactless infrared thermometer (MEM LEPU LFR30B) in the residual limb as well as in the uninjured limb of the amputee cohort and in the dominant hand used for playing of the able-bodied cohort, as it can be indicative of alterations in blood flow and muscle activity [28, 66, 67].

The embodiment and agency of the virtual superimposed arm/tentacle was evaluated using an altered **Prosthesis Embodiment Scale (PES)** by Bekrater-Bodmann [68], in which "prosthesis" was swapped out for "virtual arm", and which consists of 10 items across 3 subscales for ownership (feeling as if the virtual arm belongs to oneself), agency (feeling in control of the virtual arm), and anatomical plausibility (the virtual arm being in an anatomically correct position relative to the user), with ratings from -3 (strongly disagree) to + 3 (strongly agree) [69, 70].

The usability evaluation of PhantomAR involved a single session of approximately 60 min being exposed to the application. The study protocol consisted of two sessions in which the participants were experiencing 4 randomized PhantomAR scenes, with the usability evaluation after both experiences and interleaved PLP NRS questionnaires (see Fig. 1). The real arm of able-bodied participants was obscured with a sleeve to prevent hand recognition by the HoloLens 2.

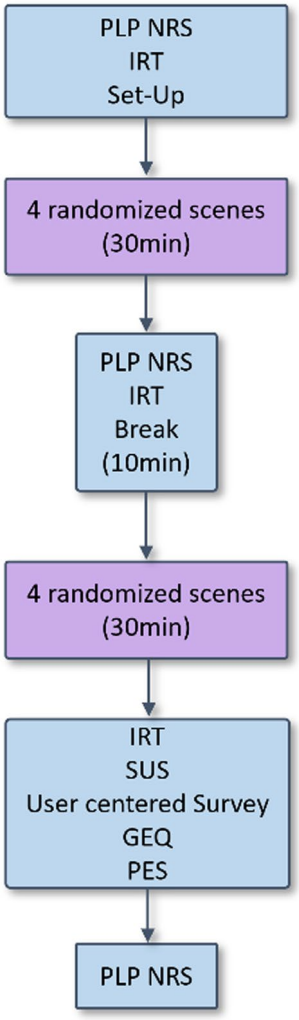

Fig. 1 Flow-chart of the study protocol. After the first PLP questionnaire the Set-Up required under 5 min, including the donning of the devices and calibration of the virtual arm. (PLP = Phantom Limb Pain, NRS = Numerical Rating Scale, IRT infrared thermometer measurement, SUS = System Usability Scale, GEQ = Game Experience Questionnaire, PES = Prosthesis Embodiment Scale)

Study setup

At the beginning of the study, participants sat comfortably in a chair in an examination room with ambient temperature of 22°C. Skin temperature was measured on the volar side of the stump and on the corresponding area on the contralateral, uninjured limb in patients and on the volar forearm in healthy participants. Patients were asked to rate their momentary PLP on the NRS scale.

The mixed reality study required a setup that was quick to implement for effective use in daily clinical practice. The equipment included a Microsoft HoloLens 2 headset on which the holograms of the mixed reality were projected, one Myo electrode armband (Thalmic Labs, Toronto, Canada, Note: discontinued by Thalmic Labs) and two Mbient Lab MMRL inertial measurement units (MBIENTLAB INC, San Jose, USA). The Myo armband featured 8 EMG electrodes, and a vibration motor for haptic feedback. MMRL sensors incorporated a 9-axis IMU. The setup was entirely wireless and battery-operated. Participants wore the Myo armband and an MMRL sensor on the residual lower limb and another MMRL sensor on the upper arm (see Fig. 2).

Interaction scenes within the application were designed to automatically adjust to available room sizes and shapes, ideally within 10–20 m^2. Upon wearing the HoloLens 2, the virtual arm and myoelectric controls were calibrated, saving the user's profile, including scale and relative shoulder position, in the app. This initial setup took under 5 min and was only necessary once.

Participants did not receive any further information beyond the essential instructions needed to operate and

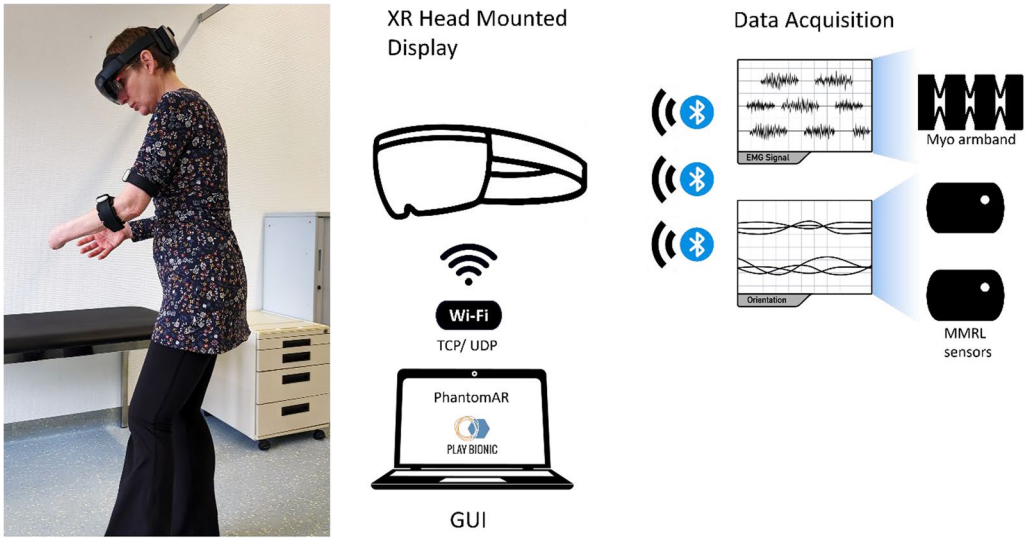

Fig. 2 The PhantomAR system set-up consists of the extended reality device Microsoft HoloLens 2, the Thalmic Myo electrode armband which transmits EMG signals, and 2 MMRL sensors for orientation data of the superimposed digital arm. The set-up is completely wireless and does not restrict movement while patients can explore the virtual environments

interact with the PhantomAR and were instructed simply to explore their environment which they did by walking around and interacting with various virtual and real elements.. Specifically, they were not provided with any details about the expected therapeutic effects on phantom sensations or pain. This approach was taken to minimize expectation bias and ensure that participants' experiences and ratings were not influenced by preconceived notions about the intervention's effectiveness.

After navigating the first four interaction scenes, patients were asked about their PLP. After playing another set of 4 random interaction scenes, participants evaluated the PhantomAR application, completing the SUS, the User centered survey, the altered PES and the GEQ. Their temperature was taken again at the same location as during the beginning of the trial and they were asked one last time about their momentarily PLP.

Data analysis

Data were processed in Matlab version R2022b (Natick, Massachusetts: The MathWorks Inc). The Wilcoxon signed-rank test, as non-parametric test for related samples, was used for the following analyses: comparing medians of pre- and post-intervention NRS scores for PLP and the Short-Form McGill Pain Questionnaire (SF MPQ) Pain Rating Index (PRI); analyzing skin temperature changes in both the able-bodied and patient cohorts before and after the intervention; and comparing scores on the Embodiment Scale between amputees and able-bodied participants. The Mann–Whitney U test was used to determine differences between independent samples, such as the scores from the Game Experience Questionnaire (GEQ). Additionally, the Pearson correlation coefficient was employed to analyze the correlation between changes in skin temperature and PLP scores before and after the intervention. Given the small sample size, the level of statistical significance was consistently set at $p < 0.01$.

Implementation

We designed and implemented 7 different environments for users to explore, as well as a separate graphical user interface for therapists and patients, using the game development platform Unity 3D and the Microsoft Mixed Reality Toolkit. The PhantomAR application was installed on the Microsoft HoloLens 2 and connected via Bluetooth to the Thalmic Myo electrode armband and the MMRL IMU sensors. The optional graphical user interface (GUI) for therapists was running on a laptop and connected to the PhantomAR HoloLens session via WI- FI.

Game design and interaction scenes

The game design focused on immersion while minimizing mental stress, frustration and discomfort for patients, which are factors that could adversely affect PLP and the EMG control due to high muscle tension. Therefore, a curiosity driven gameplay was chosen, where the patients can freely explore an interesting and interactive environment without the possibility of failure or underperforming.

To allow patients to immerse themselves into the mixed reality experience, the rehabilitative exercises were integrated into various playful scenes (see Table 2). These scenes were designed without specific end goals, timers, or scoring systems. Instead, patients were encouraged to explore their surroundings with inquisitiveness, discovering the possibilities within each scene. This exploration involved touching, moving and resizing objects, interacting using one or both hands, and engaging with multiple objects simultaneously (see Fig. 3). The focus was on experiential learning and interaction rather than achieving specific objectives, fostering a more immersive and less pressured environment.

Spatial mapping

The HoloLens 2 supports automatic spatial mapping, enabling it to scan floors, walls, and tangible objects such as tables or smaller sized objects, allowing for the integration of virtual content with the real-world while adhering to height, width, or margin requirements. This feature is instrumental in making PhantomAR an environmentally aware application and supports various game mechanics, including the generation of plants on surfaces, interacting with floors, walls and ceilings, i.e. bouncing a ball on the floor, and placing virtual objects onto physical ones. However, Microsoft's toolkit provided only basic surface data, which could occasionally extend beyond the current room. Therefore, a specialized wrapper layer was

Table 2 Overview of the interactable scenes that were used in the study

Scene	Difficulty	Description	MyoControl
Aqua	3	Underwater simulation with interactive elements such as fish, algae, and corals integrated into the room's spatial mapping environment. A treasure chest positions itself on any flat surface detected within the space. Participants are tasked with touching and combining virtual objects, which are designed to exhibit unexpected behaviors upon interaction	Interaction with both virtual and real hand simultaneously is possible, but not necessary
Liquid Creatures	3	Generation of sigils on the walls and a central virtual pillar on the actual floor. Participants interact with simulated liquids, eggs, and rune stones to initiate the spawning of various creatures within the space. Some of these virtual creatures are programmed to exhibit follower behavior, reacting to the participant's movements	Interaction with both virtual and real hand simultaneously is possible, but not necessary
Pipes	2–3	Virtual levers are algorithmically generated on the walls of the environment. When these levers are activated by the participant, a virtual pipe appears, necessitating connection to an existing network of pipes through a series of grab-and-rotate interaction. Successful connections trigger the release of steam clouds	Interaction with both hands simultaneously is required
Space Music	2	Set within a virtual space environment, this scenario creates interaction with planets that produce musical outputs. Participants can create simple melodies by engaging with objects they place in the planet's orbit	Interaction with both hands simultaneously is required
Fruit Picking	2	Collecting of virtual fruits that are algorithmically spawned within the environment, including less conspicuous locations such as under tables. The system allows participants to manipulate the size of these fruits by using a bilateral hand grip, enabling the fruits to fit into a designated collection basket	Interaction with both virtual and real hand simultaneously is possible, but not necessary
Drawing	1	Create three-dimensional drawings within the virtual space or on surfaces. This interaction is predominantly unilateral, with the augmented hand designated for the act of drawing. The selection of colors is managed by the contralateral hand, providing a more complementary role	Predominantly unilateral interaction with the virtual hand
Shooting	1	Participants aim and fire at target objects, represented by virtual flowers that are programmed to wilt and respawn upon being hit. The system enhances hand–eye coordination through the implementation of an aiming ray, guiding the participant's actions	Predominantly unilateral interaction with the virtual hand

Each scene contains a distinct environment and follows different rules and interaction mechanisms to sustain patient engagement and curiosity. The interactive elements within each scene can be manipulated using both the virtual and the physical hand

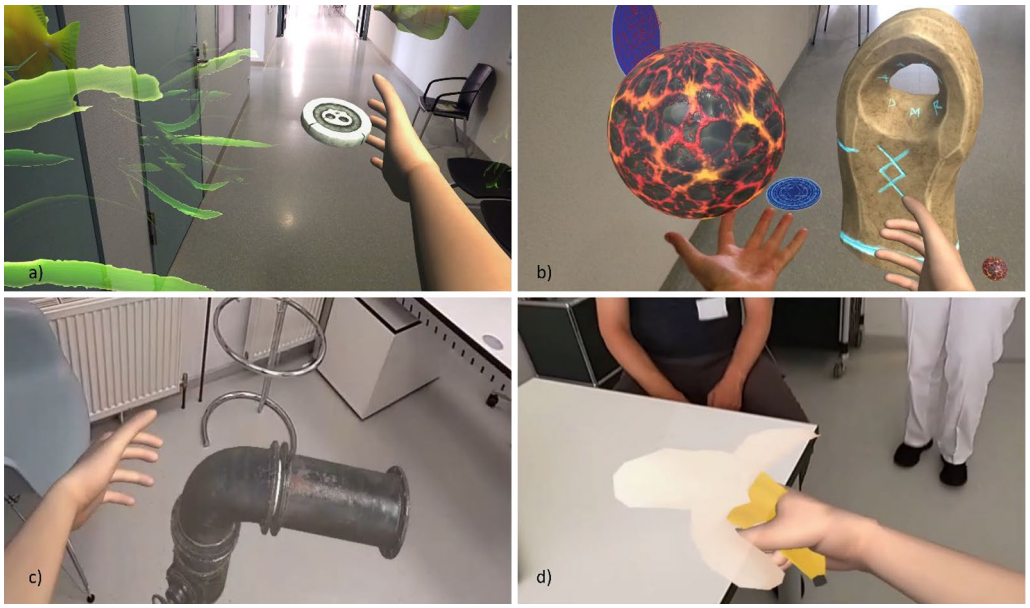

Fig. 3 Screenshots of **a** Scene Aqua, which presents the player with various underwater elements to encourage interaction, i.e. the coin can be grabbed by the virtual or healthy hand and used to trigger certain events. **b** Scene Creature companion shows the interaction with a ball of lava that is bounced between the real and the virtual hand and can be evolved into a creature. The pillar is standing on the floor recognized by spatial recognition. **c** Pipes can be placed on walls, floor, or desks and interconnected. More pipe parts can be released via a virtual lever automatically placed on a wall. **d** Different fruits can be gathered and manipulated, such as resizing or squashing them

required to identify suitable object placement locations and improve game integration and responsiveness.

Interaction with the virtual environment: arm and hand movements

Both the virtual and the intact hand were capable of interacting with virtual objects The residual limb was tracked using IMU data from two MMRL sensors positioned on the upper and lower arm. Combined with EMG data from a Thalmic Myo Armband on the residual lower arm, this setup enabled the creation of a virtual arm that the patient could freely control, much like a prosthesis. Previous horizontal drift over time could be addressed using these MMRL IMU sensors [47] instead of the Thalmic MyoArmband for spatial data. The position of the shoulder was fixed in relation to the head position and was adapted to match the individual user. In case the virtual arm should not align with the patient's residual limb anymore, the virtual arm could be reset to the calibrated position with a light tap on the MyoArmband.

To enhance the naturalness of grasping movements with the virtual hand, we introduced auxiliary interaction mechanisms such as freezing the target object during grabbing and implementing a two-handed interaction for larger objects which necessitated the use of the contralateral healthy hand. The HoloLens 2 tracked the healthy hand, capturing the positions of the digits and palm, enabling them to interact with virtual objects and supporting rotating the object or resizing it. A short vibration from the Thalmic Myo armband accompanied successful grabs, reducing the time needed [42]. The virtual hand had attached colliders that closely matched its shape, enabling physical interactions with virtual objects, such as pushing a ball. Smaller objects could pass between the virtual fingers to create an immersive interaction experience.

Amputees controlled the virtual hand using a combination of IMU data from MMRL sensors and EMG signals from a Thalmic Myo Armband. The grasping action was initiated when muscle activation, recorded from two electrodes placed on antagonist/agonist muscles, exceeded a preset threshold. This EMG-based threshold controller allowed the virtual hand to open or close, with the speed of these actions being proportional to the muscle signal strength. When the patient activated the designated muscles above the threshold, the virtual hand closed; when the muscles relaxed or activated differently, the hand opened.

The control algorithm, however, is modularly adaptable and any controller, such as pattern recognition, can be easily integrated into the PhantomAR application and chosen via the GUI.

Non-anthropomorphic feedback

Beyond just replicating a human arm, we allowed for the substitution of the arm model with a virtual tentacle (see Fig. 4) Both the arm and tentacle were controlled using the same motion range via EMG. However, instead of the hand's opening and closing actions, the tentacle would extend and retract. Additionally, any wrist rotations or arm movements performed by the patients were correspondingly translated to the movements of the tentacle.

GUI and remote connection for therapeutic supervision

To facilitate therapist-led guidance and control over virtual scenarios, we developed a remote control application that operates on Microsoft Windows (Fig. 5). This optional app communicates with the HoloLens 2 via Wi-Fi, providing therapists a live video stream that mirrors the patient's mixed reality view. It enhances versatility of the therapeutic process by enabling remote manipulation of virtual scenarios, such as manual creation or resetting of objects. Additionally, the GUI serves as a tool to simplify various configuration tasks, including Bluetooth connectivity setup, EMG controller calibration, and managing patient-specific parameters. However, everything can be adjusted within the HoloLens environment itself as well.

Results

System and game evaluation

The application received a System Usability Scale (SUS) score of 89.6% (SD = 6.9) by amputees and a score of 90.8% by able-bodied participants. This score reflects a high level of usability and user-friendliness, as all scores above 68% are considered above average [71].

Fig. 4 Tentacle extending and retracting according to the myoelectric signals from the user to grasp a virtual game object

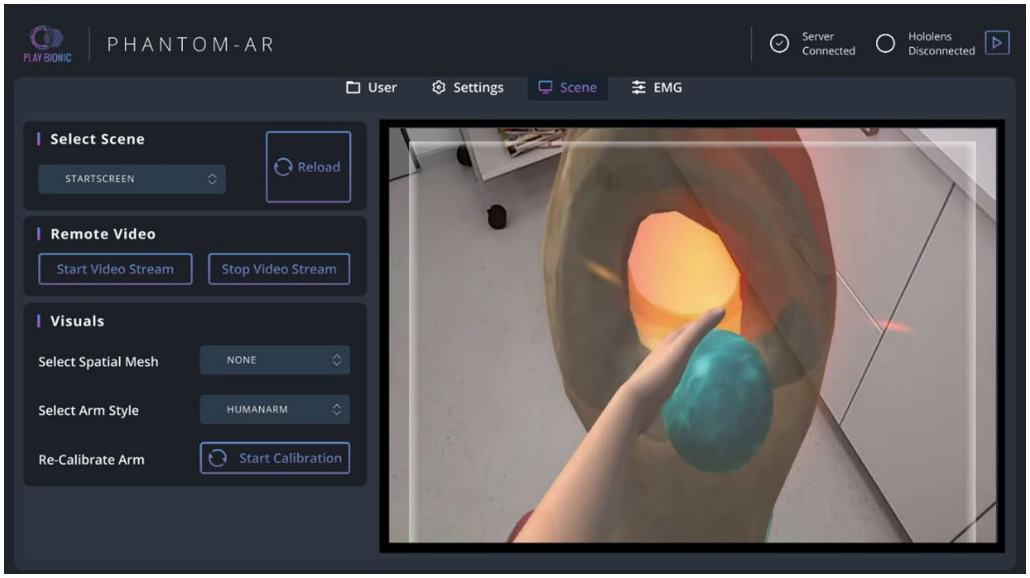

Fig. 5 Remote connected GUI. The interface has different sections for managing the user data, settings, scene control and EMG calibration. In the selected Scene section, the left side provides control over the running session, while the live stream on the right side is used to monitor the patient experience. In the lower left corner of the live stream window, the patient's stump can be seen, which is superimposed by the virtual arm

The Game Experience Questionnaire results for the patients and able-bodied participants are depicted in Fig. 6. The application received overwhelmingly positive feedback from all patients (md = 4.8, IQR = 0), with no reported negative emotions (md = 1, IQR = 0) or sensations of being overwhelmed by the challenge during gameplay (md = 1.75, IQR = 0.3). Additionally, both immersion (md = 4.5, IQR = 0) and game flow (md = 4.5, IQR = 0.3) received notably high ratings. The game experience for able-bodied participants was similar, with equal scores in the subscales positive affect (md = 5, IQR = 0), negative affect (md = 1, IQR = 0), immersion (md = 4.5, IQR = 0.18), flow (md = 4.5, IQR = 0.79). Challenge was rated slightly lower, but not significantly (md = 1.37, IQR = 0.68, p = 0.74) (see Fig. 6).

Prior mixed reality experience was limited, with 80% of able-bodied participants and all patients reporting no previous exposure.

PLP and physical reaction

Initial PLP at baseline was rated with a median of 5 (IQR = 0.75) on the NRS scale by all patients before the intervention. When questioned about their PLP during gameplay, all participants reported a decrease in their PLP while immersed in the application. However, two patients reported an increase in pain, showing a high variance in PLP during the intervention (md = 3.5, IQR = 2.5). After finishing the application patients reported a significant decrease in PLP of approximately 58%, or a median of 3 points, respectively ($p < 0.001$), between the baseline and post-intervention measurement (md = 2, IQR = 1, see Fig. 7). Ranging from 25 to 80% reduction.

Similarly, pairwise comparisons of the SF-MPQ Pain Rating Index (PRI) scores revealed a significant reduction of approximately 45% from baseline to post-intervention ($p < 0.001$; see Fig. 8).

The skin temperature shows a significant increase from before the intervention to afterwards in all conditions as presented in Table 3, its distribution can be found in Fig. 9. The difference in skin temperature between the injured and unaffected arm was on average 3 °C, with the residual limb displaying colder temperatures, and temperature increased on average 1 °C in the residual limb over the course of the intervention. There was a high variance in temperature in the residual limb of patients that ranged from 30.7 °C to 34.1 °C before and from 31.7 °C to 35.7 °C after the intervention. There was no significant temperature difference between the patients' uninjured arms and the arms of the able-bodied participants (p = 0.61).

A correlation analysis between PLP and the temperature of the residual limb before and after the intervention yielded a Pearson correlation coefficient of-0.09 and 0.19, respectively, indicating no significant linear relationship between these two variables (p = 0.83 and p = 0.64).

Embodiment

The modified Prosthesis Embodiment Scale [68], adapted to assess Virtual Arm Embodiment, revealed a high sense of agency among participants, indicating that participants felt cohesive control over the superimposed virtual arm and regarded the executed movements as their own (see Fig. 10).

Figure 10). Statistical analysis showed no significant differences in any of the subscales between healthy

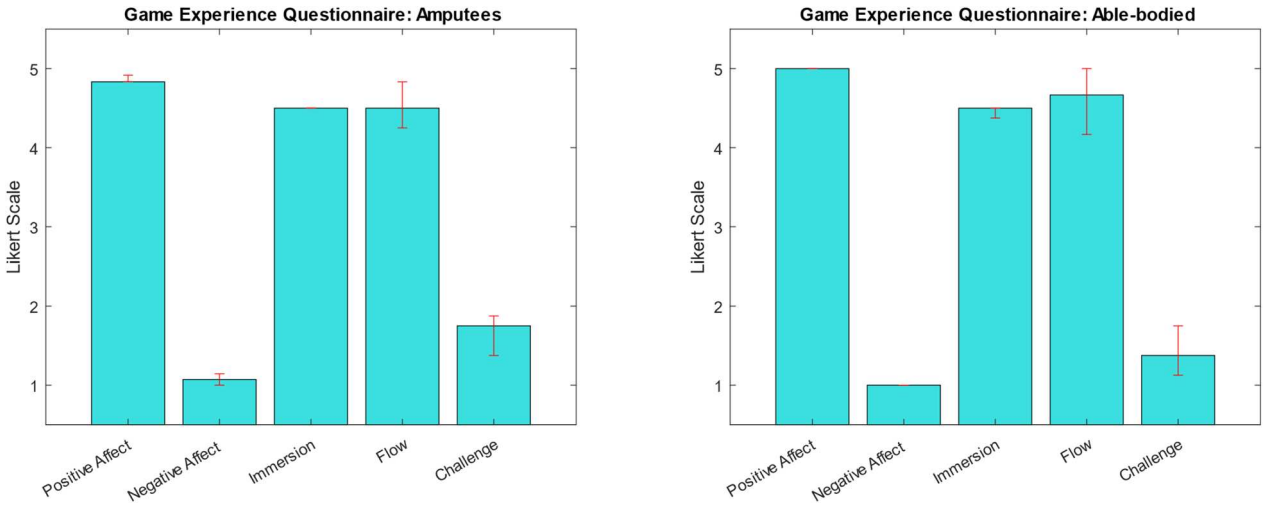

Fig. 6 The median and IQR of the game experience questionnaire on a 5-point Likert scale as rated by patients (n = 8) and able-bodied participants (n = 10) show 5 subscales for positive and negative affect, immersion, flow

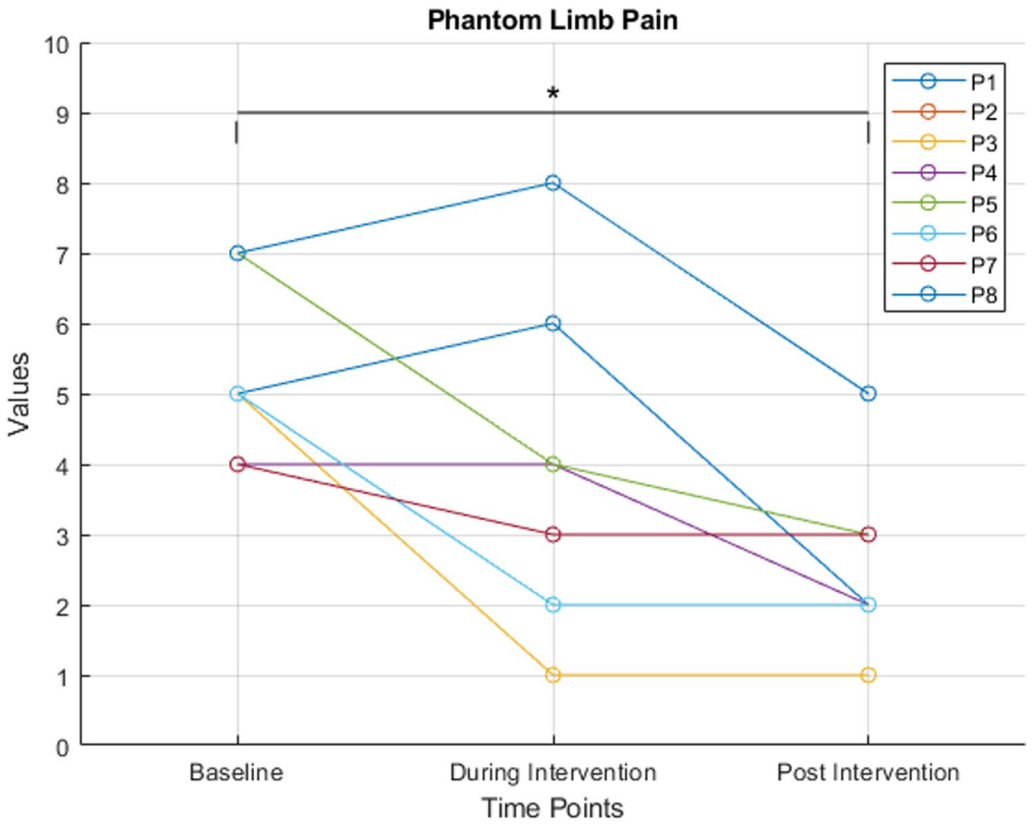

Fig. 7 Progression of PLP (n = 8) as assessed with NRS showing a significant reduction indicated * $p < 0.001$ between the baseline and post-intervention measurement. High variance in PLP NRS score was observed both at the baseline and during the intervention

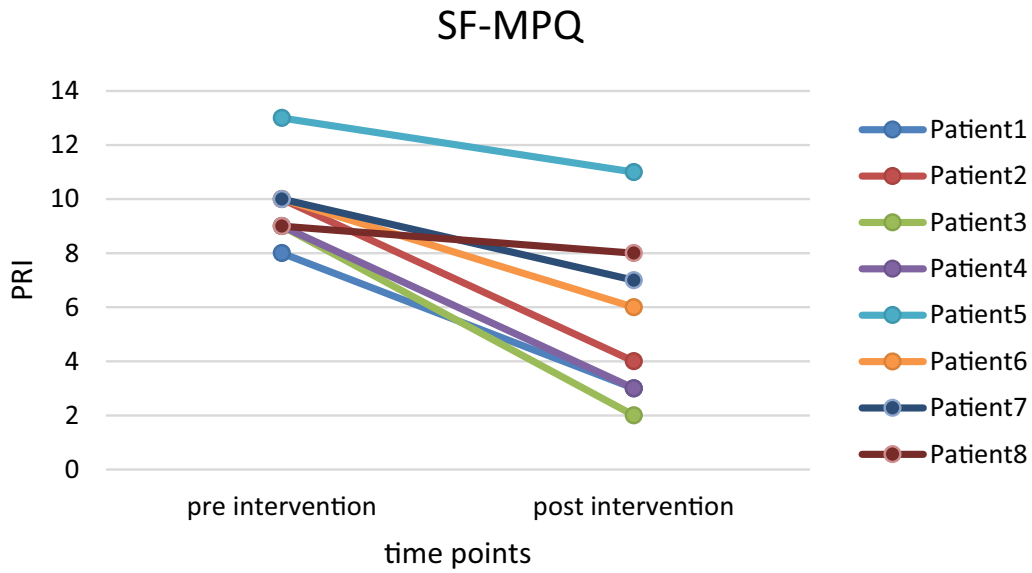

Fig. 8 Pain Rating Index (PRI) of the patients' PLP (n = 8) as assessed by the SF McGill questionnaire (SF-MPQ) showing a significant reduction from the baseline to after the PhantomAR experience ($p < 0.01$)

Table 3 Skin temperature values in patient's affected and contralateral healthy limb (n = 8) and in able-bodied participants (n = 10)

Condition	Mean temperature	Standard deviation	p
Pre—Residual Limb	31.9	1.33	< 0.01
Post—Residual Limb	32.9	1.37	
Pre—Healthy Limb	35.3	0.63	< 0.01
Post—Healthy Limb	35.9	0.44	
Pre—Able-bodied	35.6	0.76	< 0.01
Post—Able-bodied	36.2	0.45	

participants and amputees: Ownership/Integrity ($p = 0.8$), Agency ($p = 0.5$), and Anatomical Plausibility ($p = 0.15$).

Anthropomorphic representation

The use of a tentacle overlay resulted in a moderate score and high variability in ownership scores among amputee participants (md = 2.5, IQR = 2). For able-bodied participants, tentacle ownership was rated similarly (md = 2.5, IQR = 2), with no statistically significant difference ($p = 0.45$). Tentacle agency was rated highly by amputee participants (md = 3, IQR = 0.5) and similarly high by able-bodied participants (md = 3, IQ = 0.5). However, the difference in agency scores between the two groups was also not significant ($p = 0.8$). Overall, both groups showed no significant differences in tentacle ownership or agency. Anatomical plausibility shows a high variance in both amputees (md = − 0.5, IQR = 6) and able-bodied participants (md = − 0.5, IQR = 6) as this item was hard to understand in this context of using a tentacle, as some reported the objective anatomical plausibility, and some compared it to a human arm ($p = 0.8$) (see Fig. 10).

According to the user centered survey, using a tentacle for a hand was a concept which was new to all patients, but they embraced the idea and stated, that it did not necessarily need to be their hand, or any hand for that matter. They reported it was fun to explore the PhantomAR application in real life and could see the room and their augmented arm. However, they preferred an anthropomorphic representation to a tentacle.

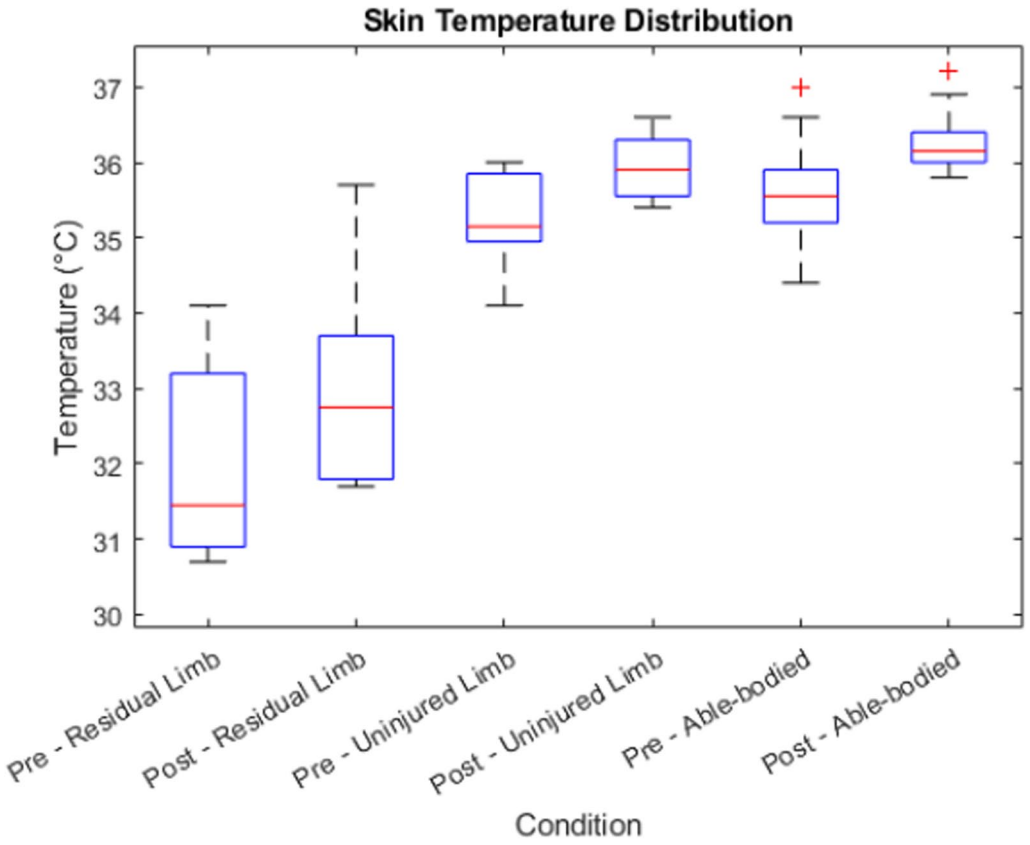

Fig. 9 Skin temperature measured on the residual limb and the unaffected contralateral limb of patients (n = 8), and in able-bodied participants (n = 10) before and after the intervention, respectively

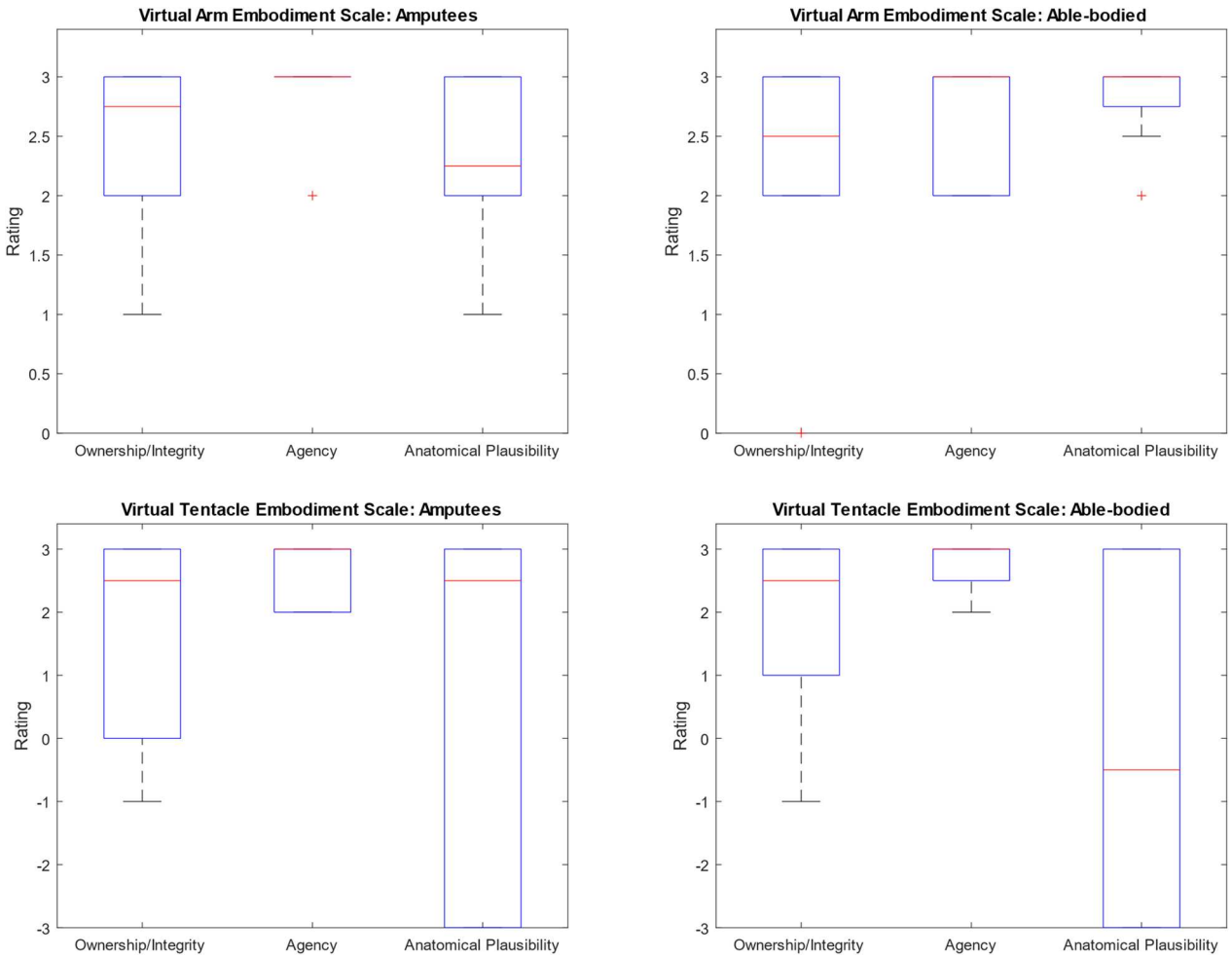

Fig. 10 The 3 subscales of the adapted Prosthesis Embodiment Scale [– 3, + 3] for all patients (left side, n = 8 and all able-bodied participants (right side, n = 10). Questions about their prosthesis had been replaced by questions about the augmented virtual arm (upper row) or the augmented tentacle (lower row)

User centered survey

Responses from all participants (n = 18) in the user-centered survey further revealed the following key observations: Users described wearing the HoloLens as comfortable, and though initially the field of view felt restricted, they soon forgot about it. They described interactions with virtual game elements in the real environment as novel, interesting and challenging, increasingly perceiving these objects as convincingly real. None reported experiencing cyber (motion) sickness during the study. The introduction of haptic feedback through the Thalmic Myo armband greatly enhanced the immersive experience of grasping objects, and participants found the controls to be intuitive.

Users commented that it was a long time since they could feel their hand and that they felt their phantom hand grow into the augmented hand. They said that they were surprised at how real everything looked and that they would like to just stay in this level (underwater level) and look around. There was not one comment that the HoloLens would be uncomfortable. When users "lost" their augmented arm, they could re-calibrate and would say "Ah, there is my hand again."

Discussion

With PhantomAR, we aimed to develop a wearable assistive therapy tool for Phantom Limb Pain (PLP) that extends traditional mirror therapy by liberating users from the restrictive seated position at a table and allowing for bimanual tasks and natural interaction with both virtual and actual objects. Addressing the complex phenomenon of PLP requires a flexible treatment approach, which PhantomAR provides through its modular design that accommodates several control methods [72]. PhantomAR was not designed to be goal-oriented, but

curiosity driven. There is no intended or evaluated task transfer from a virtual hand to a myoelectric prosthesis.

Mixed reality

By incorporating patient feedback into the design process, we ensured the clinical relevance of PhantomAR and addressed practical challenges that patients face. This user-centered approach has allowed us to optimize the system's design for clinical use. The portable and wireless nature of PhantomAR makes it adaptable for various settings, from clinics to patients' homes, with automated room detection enhancing ease of use. These features lay the groundwork for broader adoption in rehabilitation centers and at-home therapy.

Brasse et al. suggest, that mixed or augmented reality will play a significant role in future medical applications, enabling patients to perceive a fusion of virtual and real-world visuals [62]. By blending virtual projections with the real world, PhantomAR could serve as a bridge during the rehabilitation process. Specifically, it was designed to be used in the interim phase while the amputated limb is healing and before a permanent prosthetic is fitted, since using a prosthesis has been found to reduce PLP in most users [73].

PLP

While our proof-of-concept study demonstrated promise, it is clear that a single-session design cannot fully capture the long-term impact of PhantomAR on PLP. We observed high variability in how patients experienced PLP during the intervention. For instance, some patients reported immediate pain relief during active use, only to note increased discomfort shortly thereafter, followed by eventual pain reduction, which all patients reported. Engaging in active, immersive tasks in augmented reality might divert attention from pain or activate neural pathways associated with motor control, which could modulate pain perception. The potential influence of distraction or cognitive load on pain reduction might be a valuable area to explore. Therefore, performing a long-term study while also increasing the sample size can not only provide more insight on PLP but also on embodiment over time.

We observed a 58% reduction in PLP on the NRS and a 45% reduction in the PRI during this single-session intervention. A clinically meaningful change in pain perception for amputees is typically defined as an NRS reduction of approximately 2 points on the NRS or 36% [74]. In comparison, Tilak et al. reported in a previous short-term study administering mirror therapy four times a pain reduction of 3.38 ± 2.33 on the NRS in 12 patients, demonstrating comparable efficacy to our single-session results [75]. However, most other studies involved interventions lasting 2 to 4 weeks and are therefore not directly comparable. For instance, Sumitani et al. (2008) observed a 30%–50% reduction in PLP in 11 out of 22 patients after mirror therapy [76], while Foell et al. (2014) reported a 27% reduction in PLP after 4 weeks of mirror therapy in a sample of 13 patients [17].

Anthropomorphic representation

Our study's exploration of different virtual limb representations, including an anthropomorphic arm and a non-anthropomorphic tentacle, was partially inspired by real-world experiences shared by amputees. Literature pertaining to neuroplastic hypotheses for alleviating PLP highlight the relevance of prioritizing anthropomorphic visual feedback [19, 77]. The concept of stochastic entanglement as hypothesized by Ortiz-Catalan, however, predicts that pain reduction would be independent of the level of anthropomorphic visual representation [18]. In our study, while agency was high, ownership did not receive a high score for the tentacle representation.

An additional consideration is the need to disentangle which aspects of our system drives the observed outcomes, particularly with respect to embodiment, agency, and the potential PLP reduction. One possibility is that the reduction in PLP relies heavily on the user's ability to feel that the virtual limb truly belongs to them. If embodiment is essential, then only designs that closely resemble a human limb and are easily integrated into the user's body schema would be effective. In this case, the anthropomorphic nature of the virtual limb would be a crucial factor in creating a successful therapeutic outcome. Another angle to consider is whether a sense of agency—feeling in control of the virtual limb—might be more important than embodiment. And the engaging, gamified aspects of the system might boost user involvement and overall effectiveness, regardless of the virtual limb's anthropomorphism.

Temperature

The increase in mean skin temperature in the post-condition phases, such as in the 'Post Residual Limb' and 'Post Proband' groups, could be indicative of increased blood flow to those areas. An elevation in skin temperature is often associated with vasodilation, where blood vessels widen to increase blood flow. This physiological response can be a result of various factors, including increased muscle activity. The difference in temperature between the residual limb and unaffected site of 3 °C corresponds to previous findings in upper and lower limb amputees alike [67, 78] and was expected, because stump vascularization is affected by amputation and the limited activity of the residual limb. Our findings indicate that elevated PLP scores prior to the intervention correlate

with increased temperatures in the residual limb. In the context of rehabilitation or physical therapy, variations in skin temperature may serve as markers for enhanced blood flow or elevated muscle engagement, aligning with common objectives of these therapeutic interventions [79, 80].

In our study, the use of an augmented reality (AR) system inherently engages the sense of embodiment, as participants interact with a virtual limb that may feel like an extension of their body. This could mean that the temperature changes we observed might not be attributable to reductions in pain but could also be influenced by shifts in the participants' sense of ownership and embodiment of the virtual limb [81].

Bimanual interaction and myoelectric control

Although PhantomAR was not explicitly designed for myoelectric prosthesis training, its modular architecture makes it suitable for that purpose. By adapting to various control schemes, whether threshold-based or machine learning-driven, PhantomAR can support patients in preparing for prosthetic use.

The latency of the movement of the real arm to the visual representation of the corresponding virtual arm was not directly measured, but for arm movements, there is no noticeable lag. The latency is assumed to be below 50 ms, as the data is received from the MMRL sensors in real-time every 10 ms and translated to the virtual arm position within the next frame. A comparably low latency has not yet been reported in other studies, in which the latency was 500–800 ms when controlling a virtual arm using custom IMU sensors [42].

Immersion could be increased from a technical perspective by creating a spatially coherent experience of the virtual and real world that are responsively interacting with each other and underlying it with haptic feedback.

In a future study, to enhance the precision of arm tracking when rotating the head independently from the shoulders, a third MMRL sensor will be employed to monitor shoulder position, thereby creating a more accurate representation and adding additional Degrees of Freedom to the internal model of the patient's arm, which could further improve agency and embodiment. Currently, PhantomAR is exclusively available for transradial (forearm) amputees, but in the future, we plan to extend it to transhumeral (upper arm) amputees as well.

Limitations

The findings presented in this feasibility study are based on a single group analysis of 8 amputees. We acknowledge that the lack of a control group limits the strength of any conclusions regarding efficacy compared to conventional therapeutic approaches. A longitudinal study is needed to further investigate the findings. Reliance on self-reported measures for PLP intensity, embodiment, ownership, and agency might introduce a subjective bias. Consequently, the results and analyses should be considered in light of this. Moreover, the restricted field of view of the Microsoft HoloLens 2 could limit the immersive experience, especially when users move outside the central vision area.

Conclusion

PhantomAR represents an innovative application in the treatment of Phantom Limb Pain, offering an immersive mixed reality experience that extends beyond the static limitations of traditional Mirror Therapy. By leveraging the capabilities of the HoloLens 2, PhantomAR enables amputees to engage in bimanual, full-body interactions with both anthropomorphic and non-anthropomorphic virtual limbs. The findings demonstrated a significant reduction in PLP following a single-session intervention, high usability, and an immersive experience that captivated users. Haptic feedback further enhanced the sense of immersion and realism, with users reporting a meaningful reconnection with their phantom limb. These preliminary findings emphasize the importance of developing flexible, user-centered, plug-and-play therapeutic tools for amputees. A longitudinal, controlled study is needed to validate these findings, assess the long-term impact of repeated interventions, and evaluate the sustained effects of PhantomAR on PLP, embodiment, and user engagement over time.

Abbreviations

GUI	Graphical user interface
GEQ	Game experience questionnaire
IMU	Inertial measurement unit
IRT	Infrared thermometer measurement
NRS	Numerical rating scale
PES	Prosthesis embodiment scale
PLP	Phantom limb pain
PRI	Pain rating index (SF McGill)
SUS	System usability scale

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12984-025-01554-7.

Additional file 1.

Additional file 2.

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Author contributions

CP did the conceptualization, design, investigation of the study, conducted formal analysis, managed resources, curated data, developed software, created visualizations, administered the project, acquired funding, and drafted the manuscript. KE contributed to software development, formal analysis, data

curation, and acquired funding. MB contributed to software development, data curation, and providing a critical review of the manuscript. ZW, XL, and TS were dedicated to software development. AD and JK provided critical review of the manuscript and supervision. HK provided supervision, funding acquisition, and critical review of the manuscript. All authors have read and approved the final manuscript for publication.

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Availability of data and materials
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Participant recruitment for the study was conducted in compliance with the Declaration of Helsinki and followed the ethical guidelines by the University of Tuebingen, Germany, under the positive vote number 181/2020BO1. Prior to the initiation of the study, informed consent was obtained from all participants.

Consent for publication
Consent on publishing any data, including images or videos, has been obtained from all participants via the institutional consent form.

Competing interests
The authors declare no competing interests.

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Selbständigkeitserklärung

Hiermit versichere ich, dass ich die vorliegende Arbeit selbständig und nur mit den angegebenen Hilfsmitteln angefertigt habe und dass alle Stellen, die dem Wortlaut oder dem Sinne nach anderen Werken entnommen sind, durch Angaben von Quellen als Entlehnung kenntlich gemacht worden sind. Diese Arbeit wurde in gleicher oder ähnlicher Form in keinem anderen Studiengang als Prüfungsleistung vorgelegt.

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