The Impact of Implicit and Explicit Feedback on Performance and Experience during VR-Supported Motor Rehabilitation

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Figure 1: Experimental scenario. Top left: Participants were exposed to the VR simulation while using the gait robot (Lokomat). Top center: Avatar embodiment. Virtual handles (in light blue) mimic the position and shape of the real physical handles to generate plausible hand actions during walking. Top right: Explicit visual feedback signaled at the trainer's feet. Bottom left: Same explicit feedback signaled at the patient's feet. Bottom center: Alternative feedback example. Bottom right: Emoticon feedback.

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Abstract

This paper examines the impact of implicit and explicit feedback in Virtual Reality (VR) on performance and user experience during motor rehabilitation. In this work, explicit feedback consists of visual and auditory cues provided by a virtual trainer, compared to traditional feedback provided by a real physiotherapist. Implicit feedback was generated by the walking motion of the virtual trainer accompanying the patient during virtual walks. Here, the potential synchrony of movements between the trainer and trainee is intended to create an implicit visual affordance of motion adaption. We hypothesize that this will stimulate the activation of mirror neurons, thus fostering neuroadaptive processes. We conducted a clinical user study in a rehabilitation center employing a gait robot. We investigated the performance outcome and subjective experience of four resulting VR-supported rehabilitation conditions: with/without explicit feedback, and with/without implicit (synchronous motion) stimulation by a virtual trainer. We further included two baseline conditions reflecting the current NonVR procedure in the rehabilitation center. Our results show that additional feedback generally resulted in better patient performance, objectively assessed by the necessary applied support force of the robot. Additionally, our VR-supported rehabilitation procedure improved enjoyment and satisfaction, while no negative impacts could be observed. Implicit feedback and adapted motion synchrony by the virtual trainer led to higher mental demand, giving rise to hopes of increased neural activity and neuroadaptive stimulation.

Index Terms: Human-centered computing—Visualization—Virtual reality

1 Introduction

Virtual Reality Therapy (VRT) is known to provide effective alternatives to various traditional therapy approaches. For example, patients suffering from motor impairments could greatly benefit from sophisticated VRT training methods. However, it is crucial to investigate essential mechanisms and gain a deeper understanding for application designs that maximize the experience, performance, and ultimately therapy outcome without negative consequences.

Motivation and continuous, repeated exercise are important key factors in successful rehabilitation to induce neuroplasticity [29, 31]. VR has gained popularity as a medium for various therapeutic interventions and support use cases, accompanied by several rehabilitation frameworks [29]. For example, with regard to motor rehabilitation, a meta-review by De Rooij et al. showed that VR-based therapies are capable of enhancing gait and balance [17]. Overall, VR-based therapy systems provide notable therapeutic advantages, including fine-grained regulation of dosage and repetition, the availability of goal-oriented tasks with multiple levels of complexity, vivid and enriched environments, and assorted feedback options for

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both therapists and patients [43, 45, 69]. Furthermore, VR-based rehabilitation systems can counteract boredom and make therapy more pleasurable and engaging for the individual [59, 70]. In previous approaches of walking-based therapies, patients often simply walked in a virtual environment (VE) [63] or were tasked with avoiding virtual obstacles located along the walking path [71]. Previous work found that VR-based rehabilitation could potentially improve stimulation, mobility, and self-efficacy. These approaches often also included virtual trainers to guide users during exercises [15, 32], motivate the patients [24], and/or give verbal and non-verbal feedback [32, 40].

Previous work primarily focused on presenting a plausible and compelling virtual exercise environment in addition to motivational aspects to engage patients. While in general these approaches were quite successful, there is still a lack of detailed knowledge about the potential design space to foster specific desired therapy outcomes. VR provides a myriad of potential feedback mechanisms. However, which of these are most effective in improving the performance for a specific goal tackled by both the general and the individual therapy session? While one could assume that feedback generally has a positive impact, it has yet to be understood how typical feedback interactions in the physical world and classic human-human communication could be utilized by a virtual simulation.

In this regard, the importance of virtual feedback and its comparison to traditional therapy have not been thoroughly investigated. For example, in the physical world, trainers assisting patients who are exercising on a gait robot are usually mobile and unrestricted. They are free to point out and demonstrate specific movements to the patient without being forced to move alongside the patient. This process cannot easily be transferred to VR-supported gait applications that include dynamic (i.e., moving with gait) environments without breaking the plausibility. It is therefore of interest to design and evaluate feedback metaphors that comply with VR-supported rehabilitation approaches.

Explicit feedback typical for therapy and motor rehabilitation in the physical world consists of a variety of either system-generated signals (lamps, sounds, alarms, etc.) or communicative acts by the trainer and therapist. The latter include verbal corrections, nonverbal demonstrations of movements, physical touch-based corrections, and a combination of all of these. VR provides the unique possibility to additionally use implicit forms of feedback to induce specific motion adaptation processes. Similar to mirror therapies, it may be beneficial for patients to observe and imitate movements.

Implicit feedback through motor mimicry is, in theory, also an option for NonVR therapies (extending existing mirror therapy approaches). In practice, however, such an approach does not scale well to the physical world, where a therapist would be required to move continuously with each patient throughout the entire working day. Additionally, stationary robot-based gait-rehabilitation is nearly impossible in cases where the patient performs a walking motion but physically does not move. In such scenarios, a therapist must continuously demonstrate the target movement to the patient while walking on a similar stationary device. Hence, VR-based therapy approaches appear to be better suited to simulate a combination of such explicit and implicit feedback. For this reason, we became interested in finding an appropriate design to transform and integrate explicit and implicit feedback in VR-supported simulations.

The present work aims to (a) develop a VR-based gait rehabilitation system including implicit and explicit feedback; (b) investigate the influence of feedback (implicit and explicit) on the performance and experience of patients; and (c) explore the applicability of the system for therapeutic treatment.

Subsequently, our main research questions were to investigate:

RQ1: How does explicit feedback impact the user performance and subjective experience?

RQ2: How does implicit feedback in the form of motion synchrony impact the user performance and subjective experience?

1.1 Contribution

This paper presents the design and evaluation of two feedback variants for VR-supported therapy: (1) explicit feedback as a virtual adaptation of traditional approaches, making use of affordances for dynamic points of interest, and (2) implicit feedback in the form of motion synchrony to trigger mirror neuron brain activation. We report the effects on gait rehabilitation outcomes for patients with neurological gait impairment. To do so, we developed an immersive VR-based gait rehabilitation system consisting of a dynamic and versatile VE, a virtual trainer to accompany an individual during walking, and the ability to provide auditory and visual feedback. Our evaluation outcomes show that VR therapy applications not only foster enjoyment and satisfaction but may also benefit from additional feedback integrations. Our findings imply that feedback may be a critical mechanic of VR-supported rehabilitation systems to improve treatment quality and that implicit feedback generates a higher mental demand, giving rise to hopes of increased neural activity and neuroadaptive stimulation.

Our outcomes have implications for VR and for medical communities. They substantiate the theory that presenting explicit feedback in visual/verbal form during a rehabilitation session may improve motivation and the success of the treatment. Further, we found indications that implicit feedback may stimulate the mirror neuron system and can result in higher mental demand and perceived effort, therefore may have beneficial effects for the rehabilitation procedures and guide further research. Additionally, we illustrate that our VR-based rehabilitation environment provides an enjoyable and applicable training environment that may therefore support better therapy outcomes and increased patient satisfaction.

2 Related Work

2.1 VR-based Rehabilitation

VR-based rehabilitation is shown to have benefits over traditional rehabilitation methods in terms of motor learning concepts, such as real-time multi-sensory feedback and task variation [37, 44, 58]. Previous work showed that such interventions provoke the healing of motor learning and reorganize the neural architecture [14, 58, 77]. VR as a supporting rehabilitation technology can enhance the motivation [13, 37, 44] and confidence of patients performing gait tasks. Overall, extensive research shows that VR can be feasible and effective when integrated into a clinical procedure [13]. Yang et al. [75] assessed the influence of VR treadmill therapy on the community ambulation ability in stroke patients. They developed a VR application consisting of different scenarios (e.g., park stroll, obstacles striding cross) with differing levels of complexity. The VE was displayed on three 239-cm wide joined screens while leg movements were tracked using an electromagnetic system. The study demonstrated that virtual reality-based training is safe, motivational, and helpful for stroke patients. In our previous work we presented an immersive VR gait rehabilitation system to augment motivation and therapy effectiveness [25]. The VR system was composed of a VE including natural landscapes, an HTC Vive head-mounted display (HMD), and gait tracking sensors. We showed that such a system could provide sufficient acceptance and potentially improve user experience. Furthermore, Kern et al. compared conventional gait therapy with VR gait therapy in terms of motivational effects and physical workload [36]. For this purpose, they developed a VR rehabilitation application employing an HMD and motion sensors. Their system included a gamified approach (using a virtual dog as a companion). Healthy participants reported increased motivation and further advantages for gait rehabilitation. Zimmerli et al. aimed to develop and evaluate a VR application to enhance patients' motivation during gait treatment. The therapy application included various environments and tasks with different complexity levels. A 42-inch screen was placed in front of the robotic-gait assisted device (Lokomat) to display the VEs. The outcomes demonstrated that the VR

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application provided higher motivation during training and enhanced the gait activity of the patients [79]. In line with previous research, Calabro [11] found that the integration of VR with a robotic-gait assisted device enhanced balance and gait in patients. Moreover, a study by Bergmann and colleagues reported that in addition to improved motivation, the level of acceptability of robotic-assisted gait training devices utilizing VR was higher among stroke patients [5].

In summary, while these studies provide useful insights into the therapeutic support afforded by VR, they lack concrete and systematic investigation into the feedback provided to users.

2.2 The Role of Explicit Feedback in Rehabilitation

Several prior studies from assorted rehabilitation areas related to the present context may provide useful insight into the potential role of feedback in rehabilitation success. For example, research shows that the performance of an exercise as well as the number of attempts made at the exercise both improve when visual feedback was presented to the individual [3]. Further research reported that visual feedback in therapy regimens enhanced sports performance and moreover, motivated individuals to maximize their endeavors [12]. Bickers et al. found that verbal encouragement augmented the performance of a motor endurance task [6]. Banz et al. compared the effectiveness of computerized visual feedback and verbal instructions on the treatment outcome when patients performed robotic-assisted gait training [4]. Patients with neurological gait disorders performed the therapy following the instruction of a physiotherapist while observing the visual feedback. The study reported that the patients were more motivated and concentrated on their walking when the visual feedback was presented to them. Computerized visual feedback could therefore be a valuable tool to increase encouragement, participation, and motor output during rehabilitation. The virtual training environment may depict auditory, visual and haptic display feedback [52, 60]. Research shows that both feedback and the intensity of training influence patient motivation. In addition, positive and instant feedback within VR rehabilitation applications enhances confidence and training compliance [26, 72]. Wille et al. [73] aimed to develop a VR-based pediatric interactive therapy system for children with upper limb motor dysfunctions. The system provided upper limb exercises, along with instantaneous feedback regarding the performance of the children. Patients with upper limb impairment took part in the pilot study for nine sessions. The study had promising results in terms of increasing patient engagement and enhancement of hand function.

Overall, these findings indicate the potential benefit of feedback metaphors integrated into VR-supported therapy applications. While some options may involve gamified feedback approaches (e.g., [36]), we specifically focused on feedback provided by, or in combination with, the virtual trainer in our application.

2.3 Virtual Trainers

Virtual trainers in the form of agents (i.e., virtual characters driven by algorithms) have the ability to provide visual and verbal feedback to individuals [2]. According to the research of Zanbaka et al. [78], the reactions of people toward a virtual human in comparison to a real human are similar. Virtual agents can generally be employed for training purposes [2] and so VR may provide fresh opportunities for communication training. For example, medical students may have the chance to observe communication between a patient and medical doctor using a VR device, providing a high level of immersion [33]. Chua and colleagues [15] developed a VR Tai Chi training application that included a virtual coach placed in front of a student. The study found that observing and mimicking the traditional Tai Chi instruction performed by the virtual teacher afforded a better outcome. The application did not display automatic feedback. Babu et al. [2] presented a virtual human physiotherapist framework for individualized treatment and training. The system, comprised of a Straps system for tracking and improvement of 3D position of the color markers [32], allowed individuals to practice at home. The virtual trainer demonstrated to users the correct way of performing an exercise while providing verbal and non-verbal feedback to users. In a further study, we designed a VR-based rehabilitation system containing a VE with different landscapes and a female virtual trainer [24]. The female trainer provided instruction and motivational dialogue to users. Kouris et al. [40] developed a virtual balance treatment system to encourage people with balance disorders. The system offered a virtual coach who monitored individuals' activity and provided real-time feedback to users to perform therapy exercises correctly.

Various approaches have integrated virtual trainers in supportive systems. These have shown great potential in explicit feedback provision. However, in this paper, we aimed at investigating more implicit forms of feedback using the motion of virtual trainers as a feedback expression. To this end, we looked specifically at the activation of the mirror neuron system to support rehabilitative processes. We examined how we could implement such activation affordances as implicit feedback methods in rehabilitation scenarios.

2.4 Mirror Neuron Stimulation and the Role of Implicit Feedback in Rehabilitation

Previous findings and the discovery of the mirror neuron system argue that mirror neurons are activated not only when individuals perform motor actions, but also when they listen to or see similar actions [21, 62]. The integration of mirror neuron science in therapy brought promising outcomes in neurorehabilitation [19]. Franceschini et al. reported that action observation therapy can be beneficial in the rehabilitation of stroke patients [20]. The purpose of the study was to evaluate the impact of action observation treatment in upper limb rehabilitation. For this purpose, patients observed videos containing everyday hand actions and imitated similar actions. The study showed that the structures containing mirror neurons were provoked when individuals performed the same actions as those observed. The research of Buccino and colleagues asserted that the areas inside the mirror neuron system were activated from the time of observation until performing an activity [9].

Burns found that the healing process of gait therapy can be sped up when the stroke patients observed the motor act [10]. Park et al. [55] assessed the effect of action observation treatment on knee joint function in knee arthroplasty patients. In this clinical study, the participants were divided into experimental and control groups. In the treatment group, the patients watched video clips containing daily activities and imitated the tasks afterward. The study noted that the action observation training enhanced knee functions. A considerable amount of research employed mirror neuron system through action observation in motor learning and gait rehabilitation [8]. A study by Pelosin et al. indicated that action observation reduced the freezing of gait in patients with Parkinson's disease. In this study, an experimental group watched video clips containing schemes to avoid freezing of gait and particular activities. A control group observed a landscape scene while performing physical therapy [57]. Similar to this study, Agosta and colleagues [1] assessed action observation training on freezing of gait, motor abilities, and sickness indicators in patients with Parkinson's disease. They randomly divided patients into two groups. In addition to performing physical training, the experimental group observed an actor walking, and the control group watched a landscape video. The authors found that the motor disability was reduced, and balance results improved after four weeks of study in the experimental group. Moreover, they noticed an improvement in motor ability, walking speed, balance, and freezing of gait at eight weeks of therapy in the experimental action observation group. The results of previous work also reveal that action observation as an adjunctive treatment can enhance mobility, freezing of gait, balance function, and walking ability in rehabilitation [56].

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Table 1: The table displays the conditions of the study.

Baseline	VR	
NonVR + FB	VR + FB - Sync	VR + FB + Sync
NonVR - FB	VR - FB - Sync	VR - FB + Sync

To integrate and systematically investigate our research Questions ***RQ1*** and ***RQ2*** and the role of explicit and implicit feedback, we designed two feedback metaphors to be integrated into VR therapy applications. The explicit feedback metaphor was designed to include elements present in traditional therapy - in our case, audio feedback (criticism, motivation, activation) and an emoticon display - but adapted to apply to the VR simulation. The implicit feedback metaphor was subtly integrated into a leg motion adaptation procedure, aiming to stimulate the mental processes and subsequently improve rehabilitation.

3 Method

3.1 Design

We embedded our study into a regular rehabilitation program at the NiB Rehabilitation Center (Cologne, Germany). *The data was collected before the COVID19 pandemic*. To investigate our research questions and subsequently, the impact of explicit (**RQ1**) and implicit (**RQ2**) feedback, we constructed a within-subjects repeated measures experiment that collected data and impressions from all participating patients for all conditions.

The virtual conditions were factor structured in a 2 (Feedback, i.e., explicit) x 2 (Synchrony i.e., implicit) design. In the explicit *Feedback* conditions, participants received auditory and visual feedback inspired and extended from typical real-world feedback transposed to fit the VR simulation. Alternatively, in the control conditions without Feedback, this feedback was not presented. In the *Synchrony* condition, the virtual trainer adapted a walking motion cycle representing a motion cycle/cycle speed equivalent to the patient, see Fig. 2. In the control conditions without motion synchrony, this walking motion was asynchronous in speed and execution and independent of the participant's motion.

We compared these four conditions to two real-world baselines that represent present clinic standards to investigate the impact of the Medium. One condition was performed with verbal feedback and visual feedback in the form of emoticon faces. The alternate condition was performed without such feedback.

Since the physical trainer does not walk with the patient, there were neither synchronous nor asynchronous conditions in the physical world, and the physical world conditions acted as overall baselines. In this study we had four VR conditions - trainer synchrony with visual feedback, trainer synchrony without visual feedback, trainer asynchrony with visual feedback, and trainer asynchrony without visual feedback - and two baseline conditions, see Table 1. The order of the conditions was randomized throughout the experiment for each participant individually. Each condition was assessed on a different day.

3.2 Virtual Training Scenario

The study was embedded in a regular rehabilitation procedure. Sessions typically take about 50 minutes, including preparation. All conditions were assessed after exactly 30 minutes of gait walking time. For the VR conditions, a gait rehabilitation application was developed. Using inverse kinematics [67] and HTC Vive trackers attached to the robot (see Fig. 4), participants were represented as either male or female avatars accordingly. Patients' gait motion was replicated through the avatar. This allowed them to see their virtual legs moving in concurrence with their physical world movements and provided a simple form of avatar embodiment [38, 66]. To provide a better sense of security, the hands were bound to virtual bars,

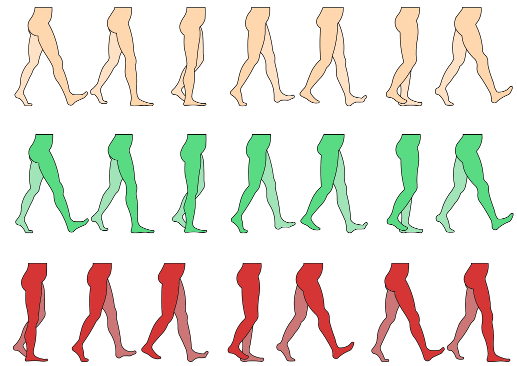

Figure 2: Gait cycle synchrony illustration. In the synchrony condition, the gait motion of the virtual trainer avatar was adjusted in speed and position to be synchronous with the patient. In the asynchrony condition, the speed was held stable and only adjusted between states (idle, walk) and the motion was not synchronized to the patient.

similar to the physical world scenario (see Fig. 1).

While walking, the speed of the translation of the virtual scene was adjusted according to the patient's gait speed. In the environment, participants passed six nature sceneries (grassland, forest, stream land, beach, farm, and desert) presented to them in randomized order. These scenes included ambient sounds. A virtual trainer (see Figure 1), driven by walk-animation cycles, walked either synchronously or asynchronously in front of the patients.

While the physical conditions make use of verbal feedback and emoticon visualizations, these were also adapted to the virtual feedback conditions. The virtual trainer provided both a social gesture (a slight turn of the head) and auditory walking instructions (e.g. "Good! Nice big steps! Keep it going!") to motivate and instruct the patients (see Fig. 1 and Sec. 3.5). A physiotherapist recorded the instruction and motivational speeches in the German language. The VR gait application presented performance feedback to patients in the forms of happy and sad emojis, similar to the physical scenario.

To adapt the traditional information provided by physiotherapists (e.g., pointing out a specific limb or instructing with exemplary movements), we designed additional virtual feedback metaphors. These were displayed as points of information animated close to the virtual trainer's legs and feet (see Fig. 1) to further support the feedback clarity. All feedback for the virtual condition was triggered by an experienced physiotherapist in line with how feedback is typically provided in a therapy session.

3.3 Apparatus

3.3.1 Gait Orthosis

The study was performed using the driven gait orthosis Lokomat (Lokomat Nanos, see Fig. 3). The Lokomat consists of a treadmill with adjustable handrails, a weight support system with support rope and frame, gait orthosis, and a patient screen for feedback. Two leg-stimulated orthoses are fastened to the legs of the users and move with predefined hip and knee joints paths [80]. Force sensors located in each joint calculate the interaction torques between the orthosis and the patient [48, 80]. Additionally, the Lokomat provides adjustable features containing walking speed, guidance force, and body weight support. These features allow the clinicians to provide specific training protocol according to condition of the patients [16, 61]. Aside from viewing and controlling the amount of supporting force, statistical information, and physiological values, the experimenter can provide emoji feedback through the patient screen turned toward the patient.

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Figure 3: Clinical setup. The Lokomat (robotic-assisted gait device). The physical NonVR scenario (left). The VR scenario (right).

Figure 4: Setup. The visual feedback presented in the physical scenario (left). Two motion trackers attached to gait orthosis (right).

3.3.2 VR Setup

The VR setup was realized with a PC (Intel Core i7-6700k 4.0 GHz CPU, 32 GB of RAM, NVIDIA GeForce GTX 1070 Graphics card), an HTC Vive HMD (2160 x 1200 pixels, 90Hz), and two HTC Vive trackers that were attached to the Lokomat orthosis (see Fig. 3). We developed the application with Unity3D. The 3D virtual therapist character was created with the Adobe Fuse CC software. For all the VR conditions, the participants could hear sounds using the Vive deluxe audio strap attached to the HMD headset.

3.4 Measures

3.4.1 Objective Performance

We collected data for the supporting guidance force controlled by the experimenter according to the patient's performance at the beginning of the experiment and in consecutive increments of five minutes. This guidance force supports the patients in gait rehabilitation using Lokomat. The guidance force can be defined from 0 to 100%. When physiotherapists set the guidance force to 100%, patients are not active and moreover, cannot deviate from the predetermined cyclical movement trajectory of knee and hip [16, 61]. Furthermore, walking with less than 100% indicates that assistance in moving the hip and knee of a patient towards the predefined path decreases, and the patient may move away from the trajectory. Ideally, this force is initially set high at the beginning of a session and gradually reduced over the course of the session. Therapists manually adapt the force according to the performance of the patient assessed by the Lokomat and shown as statistical information (force, pressure, performance) on the device. To gain further insight and to investigate any potential bias, we collected additional data including average speed, overall walking distance, and the number of pauses taken by the participant.

3.4.2 Subjective Measures

We evaluated the motivation of the subjects using the intrinsic motivation inventory (IMI) [51]. Intrinsic motivation refers to taking part in an activity for enjoyment and personal satisfaction [53]. For this study, we assessed intrinsic motivation with three relevant factors: enjoyment, pressure, and value (19 items total). The scoring of items ranged from 1 (not at all true) to 7 (very true).

For measuring the perceived task load, we used the NASA task load index (TLX) [28]. The NASA TLX was assessed with six subscales (mental demand, physical demand, temporal demands, performance, effort, and frustration) answered immediately after the walking task. Each subscale is partitioned from 0 to 20. We analyzed the raw total TLX score (see [27]) and the subscores.

Further, the satisfaction of an individual with the virtual rehabilitation system was measured using the user satisfaction evaluation questionnaire for rehabilitation systems (USEQ) [22]. The USEQ questionnaire is comprised of six items with a five-point Likert-type scale from 1 (not at all) to 5 (very much).

Finally, we asked patients to comment on their experience after each therapy session. To collect the data, we used the LimeSurvey digital survey tool. The patients answered the questions either by themselves or by communicating with an assistant that read the questions verbally and logged the respective answers.

3.4.3 Control Measures

We assessed the simulator sickness questionnaire (SSQ) [35] to investigate whether users of VR encounter sickness and unwanted side effects [7]. Each symptom was rated from 0 (none) to 3 (severe). The participants answered the SSQ questionnaire before and immediately after the gait therapy. Similar to the supporting force, the heart rate of a patient was measured at the beginning of the walking therapy (0 min) and then noted consecutively after every 5 minutes of the walking activity. We recorded the heart rate using a smartwatch worn by the patient during the experiment. We used the functional ambulation categories (FAC) instrument to evaluate the ambulation ability of the participants [30]. The FAC provides information on how much physical support an individual requires to walk safely [39] and consists of six categories ranging from dependent to independent: (0) patient cannot ambulate or needs the assistance of two or more people, (1) patient needs continuous help of one person during ambulation to support body weight and balance, (2) patient requires one person to support continuously or intermittently during ambulation with balance or coordination, (3) patient needs stand-by help or verbal supervision without manual contact, (4) patient is able to walk independently on level surfaces, however, he/she needs supervision or physical assistance on stairs, slope, or bumpy surfaces, (5) patient can walk independently on any surface and stairs.

3.5 Procedure

The participants were asked to walk using the Lokomat for 30 minutes with an average distance of 784.5 meters. The physiotherapists varied the walking speed for each patient based on the patient's health condition. The average walking speed was 1.4 km/h. Additionally, the physiotherapists instructed the patients and provided feedback in form auditory feedback (e.g. "Good! Nice big steps! Keep it going!", "The force dependency is reduced. You need to try harder", "Let's go! Keep moving the feet more forward", "Push with the forefoot and put the knee to the front and up. Let's go") and emoji feedback in both VR and NonVR, as well with additional explicit feedback form of arrows in the VR conditions.

Each participant took part in the study for six sessions and each session was implemented on a different day. Patients received the

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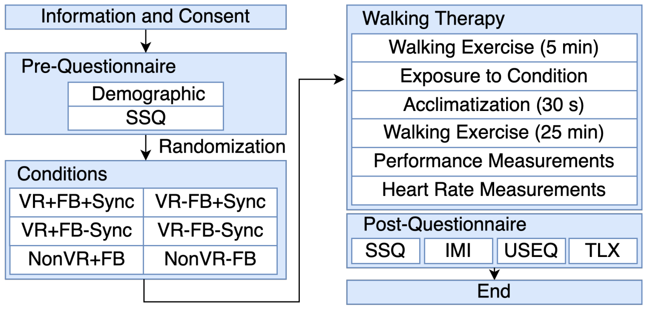

Figure 5: Visualization of the experimental procedure. A patient performed four VR conditions with/without synchrony (Sync) and with/without feedback (FB) and two control conditions (NonVR conditions) with/without feedback (FB).

guidelines of the study and gave their written consent before participating in the study. On the first day of the study, the physiotherapists asked the patients to read the study information and sign the consent paper. Fig. 5 displays an overview of the experimental procedure. A doctor at the rehabilitation center answered the demographic questions. Patients responded to the questionnaires before and after the walking therapy and could have assistance in filling out the questionnaires. After answering the first part of the questionnaires, a physiotherapist prepared the patients for the walking exercise with a robotic-assisted gait device. The preparation phase was performed with an adjustable a support belt, leg straps, weight support system, and Lokomat orthosis. In addition, a physiotherapist placed the hands of the patients on the handrails and a smartwatch on the wrist of the patient to measure the patient's heart rate.

The physiotherapist required a short time (approx. five minutes) to regulate other elements of the Lokomat (step length, range of motion, etc.) for each patient. Afterward, a patient was exposed to a randomized condition and walked for 25 minutes using the Lokomat. An experimenter measured heart rate, force, unloading weight, distance, step angle, speed, the number of times the Lokomat stopped, and the number of visual feedback emojis (happy or sad) at five-minute intervals for 30 minutes. After the walking activity, patients completed the remainder of the questionnaires. An acclimatization period of 30 seconds was designated for all conditions and in addition, patients were allowed a break at any time. No patients requested a break. In total, each subject participated in six therapy sessions and each session of the experiment took 75 minutes.

3.6 Participants

The study was carried out at the NiB Rehabilitation Center (Cologne, Germany). We recruited patients with FAC scores of 0 to 2 who required a therapist for physical assistance. The study included 27 participants with gait deficits who were using a robotic assisted gait training device. Of those, we excluded 11 patients who did not complete all trials (e.g., because of switching or aborting their therapy). Therefore, the final sample included 16 participants with an average age of $M = 49.69$ years ($SD = 19.06$; $min = 18$; $max = 79$) and a mean body mass index (BMI) of $M = 25.26$ ($SD = 3.44$). This included patients suffering from stroke (4), Multiple sclerosis (2), Spinal Cord Injury (4), Traumatic Brain Injury (3), Friedreich's Ataxia (2), and Guillain-Barré Syndrome (1). Of those, five were female and 11 male. None of the patients abandoned the study because of simulator sickness. The inclusion criteria were (1) patients with neurological disorders who cannot walk alone and use a Lokomat for their therapy; (2) patients capable of comprehending the questions and instructions; (3) patients with suitable optical and auditory acuity. The exclusion criteria were (1) patients who suffer from mental illness; (2) patients with heart disease or other serious sicknesses; (3) patients sensitive to simulator illness; (4) patients with recent operations; (5) patients who cannot talk; (6) patients with epilepsy. The data was collected before the COVID19 pandemic and according in compliance to the Declaration of Helsinki.

4 Results

For the following analysis of variance (ANOVA) reportings, we report Greenhouse Geisser corrected values where the assumption of sphericity was violated. Pairwise comparisons were performed applying Bonferroni corrections where applicable.

4.1 Performance

4.1.1 Guidance Force

The physiotherapists measured the guidance force of the right and left leg every five minutes. As a majority of the patients had the same amount of guidance force for both legs, the average value of both legs was used to analyze the guidance force.

Since the design was not strictly factorial because motion synchrony could not be tested in the physical world, we compared the factors in separate analyses. First, we performed an overall comparison of Medium (i.e., NonVR vs. VR) x Feedback (i.e., presence or absence of feedback) x Time (i.e, measurement points over time) using a mixed analysis of variance (ANOVA). To do this, both synchrony and non-synchrony data were included according to the matching feedback conditions for the VR data.

First, as expected, the mixed ANOVA resulted in a statistically significant main effect for Time; $F(1.9, 28.2) = 136.114$, $p < .001$, $\eta_p^2 = 0.90$, see Fig. 6. As expected, over time, the therapist could decrease the applied support force (see Fig. 6).

The results also revealed a significant main effect for Feedback $F(1, 15) = 136.114$, $p < .001$, $\eta_p^2 = 0.90$. When explicit feedback was presented, it resulted in less supporting force ($M = 76.52$ %, $SE = 1.72$%) compared to when no explicit feedback was present ($M = 77.22$ %, $SE = 1.56$ %). The analysis did not reveal a significant main effect for Medium between NonVR ($M = 77.63$ %, $SE = 2.36$ %) and VR ($M = 77.22$ %, $SE = 1.56$ %).

We further investigated the impact of implicit feedback in the form of motion synchrony within the VR conditions using three-way (Synchrony × Feedback × Time) repeated measures ANOVA. The results revealed no significant interaction effects. No significant main effect of Synchrony on the guidance force could be observed; $F(1, 15) = 0.0$, $p = .987$, $\eta_p^2 = 0.0$.

4.2 General Task Metrics

We investigated the general metrics of the walking task in terms of speed, distance achieved, and stops needed, see Table 2. There were no significant indications of negative impacts of our manipulations or the medium the task was performed in. Interestingly, a slightly longer walking distance could be achieved when motion synchrony was present, but this effect was not significant according to the results of an ANOVA.

4.3 Intrinsic Motivation Inventory

A Medium × Feedback ANOVA revealed a significant main effect for Medium; $F(1, 15) = 7.66$, $p = .008$, $\eta_p^2 = .382$. Pairwise comparisons revealed that the VR conditions resulted in significantly higher enjoyment ($M = 5.76$, $SE = 0.23$) when compared to the NonVR conditions ($M = 5.07$, $SE = 0.36$). No further significant interaction effects or main effects for synchrony and feedback were observed. No significant main or interaction effects were observed for the value or pressure components assessed by the IMI.

4.4 User Satisfaction

A Medium × Feedback ANOVA revealed a significant main effect for Medium; $F(1, 15) = 4.96$, $p = .042$, $\eta_p^2 = .249$. Pairwise comparisons showed that the VR conditions resulted in significantly

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Table 2: Descriptive statistics of the task metrics. $M \pm SD$ for the VR conditions with/without synchrony (Sync) and feedback (FB) and the control conditions (NonVR conditions). Average speed, distance and required stops were measured every five minutes.

Condition	Avg. Speed [km/h]	Distance [m]	Stops
1. VR+FB+Sync	1.61±0.23	801.44±155.9	1.69 ±2.15
2. VR-FB+Sync	1.64±0.19	814.21±126.4	1.13 ±1.40
3. VR+FB-Sync	1.58±0.21	767.50±96.92	1.00 ±1.82
4. VR-FB-Sync	1.56±0.22	762.12±96.80	1.56 ±1.90
5. NonVR+FB	1.53±0.15	763.69±90.04	1.06 ±1.23
6. NonVR-FB	1.62±0.18	798.03±121.7	0.88 ±0.96

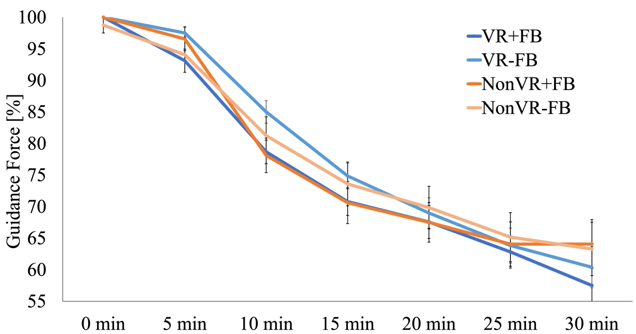

Figure 6: The graph displays the average value of the guidance force in the interaction of medium (VR and NonVR) and feedback over time.

higher user satisfaction ($M = 26.31$, $SE = 0.63$) when compared to the NonVR conditions ($M = 25.31$, $SE = 0.71$). No further significant effects for user satisfaction were observed.

4.5 Task Load

We first compared the raw total TLX score (see [27]) between both (aggregated) NonVR condition and the VR conditions.

A MEDIUM × FEEDBACK ANOVA did not show significant effects for mental demand. However, a SYNCHRONY × FEEDBACK ANOVA revealed a significant main effect for SYNCHRONY; $F(1,15) = 4.96$, $p = .042$, $\eta_p^2 = .248$. Pairwise comparisons revealed that the MOTION SYNCHRONY conditions with synchronous avatar movements resulted in statistically significantly higher mental demand ($M = 5.82$, $SE = 0.77$) when compared to those without synchronous movements ($M = 4.55$, $SE = 0.93$).

Adding to that, regarding the perceived effort, a SYNCHRONY × FEEDBACK ANOVA revealed a significant main effect for SYNCHRONY; $F(1,15) = 6.01$, $p = .027$, $\eta_p^2 = .286$. Pairwise comparisons revealed that when motion synchrony was present between the patient and avatar, it resulted in higher perceived effort ($M = 8.64$, $SE = 1.23$) compared to when synchrony was not present ($M = 6.93$, $SE = 1.07$), see Fig.7. No further significant main or interaction effects were observed in our analyses of the TLX scores.

4.6 Simulation Sickness

We investigated the difference of the total score (calculated according to the formula in [35]) between before and after the exposure to the VR simulation and therapy. No significant main or interaction effects were found. Scores ranged between $M = 10.52$ and $M = 11.69$ before the exposure, and between $M = 7.01$ and $M = 15.19$ after the exposure. There were no other indications for any sickness effects.

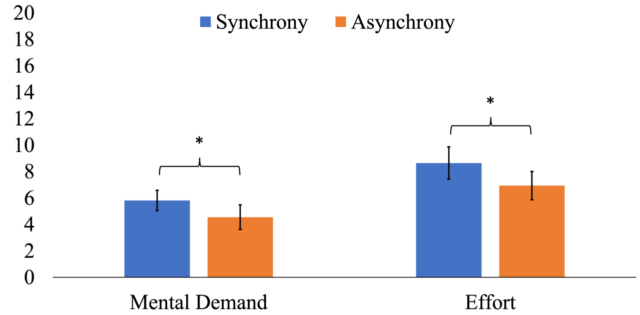

Figure 7: The scores of mental demand and effort (synchrony vs. non-synchrony). The VR conditions with synchronous walking resulted in significantly higher in mental demand and effort subscales compared to the VR conditions without synchronous movement. The error bars indicate standard error, * $p < .05$.

4.7 Physiology

No significant main effect or interaction effects were found between VR and NonVR conditions or within the VR conditions for MEDIUM, FEEDBACK , or SYNCHRONY regarding the mean heart rates or the heart rate differences (i.e., accounting for the last, respectively the baseline measure). In fact, heart rates were relatively stable throughout the experiments, therefore not indicating specific drops or increases due to VR or any of the manipulations.

5 DISCUSSION

The purpose of the study was to investigate the effect of explicit (**RQ1**) and implicit (**RQ2**) feedback on performance measures and patient subjective experience. For this purpose, we developed a VR-based rehabilitation system. We presented explicit feedback, in the form of auditory and additional visual affordances, and implicit feedback in the form of motion synchrony of the virtual trainer for a potential stimulation of the mirror neuron system. Participants evaluated their sessions in terms of motivation, task load, usability, and performance.

The physiotherapists controlled and measured the performance (guidance force) of the patients every five minutes throughout the rehabilitation session. The ideal gait treatment for the patients would be an independent movement of the hip and knee towards the predefined path with less requirement of guidance force. The results revealed that the walking dependency (guidance force) of the patients to the Lokomat reduced over time. In addition, we discovered that the applied support force reduced considerably when, in general, across the medium, explicit feedback was presented to the patients. This underlines the fact that explicit feedback plays an important role in rehabilitation procedures (**RQ1**). Previous findings show that explicit feedback enhanced the motivation and concentration of patients in gait training [4]. Therefore, in line with former studies, we could affirm that presenting explicit feedback influenced the effort as well as the performance of patients [3]. Our findings, however, indicate that this is a general effect (i.e., across media) as we could not confirm if this effect isolated in the VR conditions. In this regard, the study may have suffered from sample limitations. In addition, the explicit feedback in the VR condition may not have had a significant impact on the experience because it was in direct competition with the relatively new VR experience for the patient's attention. However, this strongly motivates future research in this direction to pinpoint, for example, necessary mechanisms. Another line of investigation could therefore be to alter the avatars be to include additional interactions with the virtual trainer on a social level, that may transmit and/or augment social motivation cues according to most efficient feedback [64, 65].

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In addition to the supporting motivation to explore explicit feedback, we found important first implications that implicit feedback triggers cognitive activity (**RQ2**). We employed the NASA TLX questionnaire to assess the perceived task load. The results revealed that in the VR conditions with displayed motion synchrony, patients reported having perceived higher mental demand and perceived effort while the physical demand remained unchanged during the rehabilitation sessions. In other words, the patients required more mental activities when they attempted to match their walking movements with the virtual trainer. Moreover, the patients worked hard to accomplish the walking exercise. We assume that the neural structure (including mirror neurons) was involved when patients observed and mimicked the walking activity. That is, in the time of copying an activity, areas inside the mirror neuron system activated from the time of observation until the execution of the activity [9]. In line with prior findings [10, 20], we believe that action observation can be valuable and helpful for gait rehabilitation. To our knowledge, no previous work has demonstrated such an effect. This presents a novel finding of our study that could be explored in several ways. First, additional user studies with healthy participants may provide more detailed insight into the potential outcomes in less restricted scenarios. Second, additional clinical studies could make use of neurophysiological measurements to explore the relationship to neurological activity by even more sophisticated trigger-functions in the VE. Finally, future investigations may target to investigate the trigger of other implicit feedback functions, such as altering patients' body representations [66, 74] to evoke the Proteus effect [46, 47, 76] that may change behaviors and actions based on the representation, to change the trainers appearance for comparable effects [42], to include heterogeneous groups of confederate training partners to increase the perceived possibility of interaction [41], or to include gamification to further increase motivation [54].

We also evaluated the resulting motivation (IMI) and satisfaction (USEQ) of the VR gait rehabilitation system. The patients were more satisfied with the VR rehabilitation approach and perceived more enjoyment in comparison to a traditional approach. The result is in line with previous studies: VR can present an interesting training environment for rehabilitation, leading to improvement in motivation and thus to better treatment consequences [23, 34, 50]. Iteration and intensity of conventional rehabilitation exercises are not adequate factors for patients to have an effective and successful recovery [17]. Motivation plays an important role in the result of the rehabilitation [49], and patients with higher motivation viewed the therapy as an important means of recovery [50]. We believe that VR-based rehabilitation decreases feeling externally controlled which can influence the intrinsic motivation of patients [18]. Thus, VR-based rehabilitation can be more valuable and effective for patients as compared to conventional therapy [37, 44, 58].

Our outcomes showed no indications of severe sickness or other negative consequences that resulted from the VR simulation. This could be explained by the fact that care was taken in (1) developing a high-performance VR simulation that is capable of providing appropriate frames per second (FPS), (2) assuring that patients walked in a straight trajectory with slow movements, (3) synchronizing the walking speed of the training device (Lokomat) and walking speed of the patients as well as the avatar, and (4) providing rest frames for the hands by using virtual bars.

5.1 Implications

Our findings provide implications appropriate for the VR and medical research that provoke further investigation. First, as expected, motivation and enjoyment were enhanced in the VR-based gait rehabilitation and patients were satisfied with using the VR-based system for treatment. Therefore, our findings are beneficial for research as well as for treatment as an additive to traditional therapy. The second implication is that, in general, presenting explicit feedback in the form of visual and auditory feedback to patients during rehabilitation influences the patient's performance. Our results affirm that the performance and motivation of patients improved in the presence of explicit feedback (we could not, however, prove that this effect was specific to the VR conditions). Therefore, explicit feedback has the potential to lead the therapy into efficient and successful rehabilitation. The third implication indicates that implicit feedback in the form of observation of the synchronous motion of the virtual trainer activated mirror neurons. Previous research revealed that action observation as a supplementary treatment improves mobility and gait ability in rehabilitation [56]. We, therefore, recommend including mirror neuron science in the VR-based gait rehabilitation applications. Future work should also consider investigating the application of VR-based assessments as methodological tools [68] to understand the underlying mechanisms of therapeutic performance.

5.2 Limitations

Although we believe we delivered a suitable application for patients, we encountered some limitations in our study. First, guidance force was controlled by the experimenter subjectively, based on her/his experience, and possibly following an acquired routine. This limitation may partly explain a potential bias for the guiding force measures. Second, in both VR and physical environments, the experimenter presented the explicit feedback manually to the participants. Further research could explore automated mechanisms of feedback. However, our argument was to keep the highest experimental control by avoiding potential third variable bias.

6 Conclusion

This paper describes our findings on the influence of implicit and explicit feedback on performance and user experience. We developed the VR-based gait system including a VE with different natural landscapes and a virtual trainer who accompanied a patient during walking and provided explicit feedback. We implemented a clinical study with patients that suffer from motor impairments. Our findings indicate that VR-based rehabilitation engages patients in therapy while no unpleasant side effects were detected. Further, the results show that explicit feedback, in general, improves patients' performance. Synchronization of movement between a patient and the virtual trainer provided higher mental demand and effort, a novel finding that we think provides the basis for future explorations. Our findings, therefore, provide novel visions and design implications for forthcoming research and therapeutic treatment.

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