Department of Precision and Microsystems Engineering

Haptic feedback in virtual reality rehabilitation for Parkinson's Disease

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Report no	:	2022.026
Professors	:	J.L. Herder, T. Vanbellingen
Specialisation	:	MSD
Type of report	:	MSc Thesis
Date	:	1st of July 2022

Article

A NOVEL VIRTUAL REALITY GLOVE SYSTEM WITH INTEGRATED VIBRO-TACTILE FEEDBACK FOR PARKINSON'S DISEASE: A USABILITY STUDY

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Abstract: Parkinson's Disease (PD) is one of the most common neuro-degenerative diseases worldwide, affecting patients' ability to perform Activities of Daily Living (ADL), such as cooking and dressing, and consequently decreasing Quality of Life (QoL). Most ADL require dexterous skills which are often impaired in PD. Pharmacological therapy is often not completely effective and has side effects. Tailored and engaging rehabilitation interventions aimed at practicing such dexterous ADL are therefore necessary at different stages of the disease. Besides the traditional physical and occupational interventions, Virtual Reality (VR) technology has proven a viable tool to facilitate such rehabilitation programs by providing flexibility in design and simultaneously creating pleasant and immersive environments. It is suggested that implementing haptic feedback into a Virtual Environment (VE) could further boost motor learning during training and improve patients' compliance to the practise. Till date, haptic feedback during VR training, has not been evaluated in PD. The purpose of the present study was twofold. First, a novel VR haptic glove system, consisting of existing VRFree gloves integrated with a Haptic Device (HD) to provide Vibrotactile Feedback (VTF) throuh the use of Linear Resonant Actuators (LRA)s, was developed. This newly developed system was then technically tested with regard to its latency, intensities and compatibility. Second, the system was evaluated on its performance and usability in both healthy subjects and PD patients by means of a novel VR grasping task. Technical tests yielded positive results; a latency of 13 +- 12 *ms* is found, the HD is able to convey different intensities and the HD produces no visually noticed interference with the VRFree gloves. The user tests revealed positive results on increased grasp performance with the VTF in terms of grasp time and smoothness among healthy subjects and a good Haptic Experience (HX) evaluation among all subjects. An average System Usability Scale (SUS) score of 75 suggest good usability of the overall system. This usability study demonstrates for the first time that VTF on the fingertips during VR rehabilitation is feasible to train dexterity related ADL in PD. Further studies will be needed to evaluate its value as a rehabilitation tool to improve QoL in PD.

Keywords: Parkinson's Disease; Rehabilitation; Dexterity; Haptics; Vibro-tactile feedback; Virtual Reality

Citation: van Wegen, M.; Adelsberger, R.; Herder, J.L., Vanbellingen, T. A novel virtual reality glove system with integrated vibro-tactile feedback for Parkinson's Disease: A usability study. *Sensors* **2022**, *1*, 0. https://doi.org/

Received:
Accepted:
Published:

1. Introduction

PD is a neurological disorder that affects over 1.2 million people in Europe alone [1]. Due to its degenerative nature, the disease causes progressive disability in patients suffering from PD. In the early stages, the most evident symptoms are movement-related, such as tremor, stiffness, problems with walking, gait and bradykinesia, slowness of movement. Cognitive and behavioural problems may arise later on, together with sleep and emotional problems, impaired balance and coordination, depression, speech difficulties and fatigue. PD can also affect dexterity and the reach-to-grasp movement [2] due to impairments in individual finger force and torque control [3] and sensory disturbances. These symptoms can cause inability of the patient to perform the essential ADL both in the beginning as well as more advanced stages of the disease [4]. Especially, proper manual dexterity is essential in the physical functioning during ADL, such as cooking, shopping, getting dressed and opening doors. Together with treatment induced complications, these symptoms can consequently affect the QoL of a patient [5]. The QoL is a multi-dimensional term which contains physical, mental and social aspects to describe the patients satisfaction of life and is an important measure of the severity of the disease [5].

Currently, a cure for PD does not exist. However, there is a wide variety of treatment strategies, including pharmacologic approaches, as well as non-pharmacologic approaches, such as Deep Brain Stimulation (DBS) and rehabilitation therapies. Medicinal dopamine replacement has proven to improve bradykinesia [6] by enhancing motor power in movements, but is not able to reconstitute the loss in coordinated motor output [7] during, for example, reach-and-grasping tasks or balance and gait and manual dexterity [2]. DBS interventions, on the other hand, have shown to positively affect motor symptoms both in gait performance, standing postural control [8] and upper limb motor performance, including dexterity [6]. Unfortunately, both dopamine treatment and DBS come with negative side effects such as dyskinesia and behavioural changes[9], [10].

Rehabilitation, including exercise interventions, has proven to significantly improve overall physical functioning and balance without the negative effects of medicinal and DBS treatment. Rehabilitation programs can be designed to address the dexterous deficits in order to enhance the practice of ADL and therefore plays an important role in improving the QoL of patients with PD [2] [11]. Because PD is a neuro-degenerative disorder, different approaches and content of the interventions are necessary at different stages of the disease. A rehabilitation program should therefore be tailored to the specific patient and their personal motor impairments [12], goal-based and focused on learning and practicing specific activities that are necessary to achieve and automatise functionality in daily routines [11].

Unfortunately, such individually tailored rehabilitation programs can be very time intensive to develop and execute with, for instance, a physical therapist. This leads to programs becoming too expensive and limited by the availability of staff. VR technology provides a solution to overcome these disadvantages [13]. VR technology immerses the user into a simulated VE by means of providing visual stimuli through a display. These technologies allow for real-time interaction between the user and the VE and enable a wide variety of possibilities in terms of design of these environments. Increasing the patients' compliance by adding factors such as sensory stimulation, cueing, feedback, rewards and pleasant environments, can enhance the effectiveness of the rehabilitation [14]. Many studies have already investigated the implementation of VR into rehabilitation. Improved motor functioning in gait and balance in patients with PD is found after VR rehabilitation [15] and exergaming-based dexterity training in VR shows feasible in improving dexterity in individuals with PD [16].

In recent years, the benefits of VR rehabilitation have been further explored by adding haptic feedback complementary to the visual and auditory feedback through the use of HDs. They create an extra dimension during the VR experience by providing haptic stimuli to the user during interactions, which can further enhance the interaction, immersion and imagination [17] in a VE. As haptic perception plays an important role in proper execution of ADL [18], the implementation of haptic feedback into VR dexterity rehabilitation for PD seems like a logical advancement. The two overarching types of haptic feedback, tactile and kinaesthetic, stimulate the perception of the human somatosensory system. The tactile perception system contains the receptors in the human skin, also known as cutaneous receptors, that can perceive mechanical stimuli, such as high/low frequency vibrations, pressure and shear deformation, as well as electrical stimuli, temperature and chemicals [19]. As for kinaesthetic perception, there are sensory receptors in muscles, tendons, and joints that describe the operational state of the human locomotor system, such as joint positions, limb alignment, body orientation and muscle tension [20]. In patients with PD, disturbances in the processing and integration of these kinaesthetic signals might partly account for the decrease in motor function [21] [22] [23]. Research suggest that this loss in kinaesthetic functions could be attenuated by engaging intact sensory mechanisms through tactile feedback [24]. In PD there seems to be an increase in both thermal and pain thresholds and a significant loss of epidermal nerve fibres and Meissner Corpuscles, the receptors responsible for low frequency stimuli [25]. Therfore, it seems obvious to target the tactile feedback on the Pacinian Corpuscles, which are the receptors responsible for the perception of high frequency vibrations [26]. Haptic feedback targeted on these receptors is referred to as VTF and is usually conveyed through the use of vibrational actuators. Studies even suggest that muscle vibrations have shown to stimulate cortical activation [27] [28]. A HD with VTF system has already proven usable in stroke patients [29] and an Augmented Reality (AR) system with haptic controller for movement assessments in PD shows potential [30]. A haptic VR system with VTF has thus far not been implemented in VR rehabilitation for patients with PD.

This paper studies the usability of a novel haptic glove system as a tool in VR PD rehabilitation aimed at practising dexterous ADL. The system consists of the existing VRFRee gloves for motion tracking and is for the first time extended with a newly developed HD that utilizes LRAs to convey VTF. The technical performance of the system is validated in terms of latency, intensity and compatibility after which the usability is demonstrated through user tests with both healthy subjects and PD patients. This is done by means of a newly designed VR grasping task in which grasping performance is evaluated and a customized questionnaire which integrates the SUS, a modified HX questionnaire, a modified User Satisfaction Evaluation Questionnaire (USEQ) and task-related questions.

First, the methodology of this study is discussed in section 2 by elaborating on the design of the HD and the set-up of the technical and user experiments. The results of the experiments are shown insection 3 and are discussed in section 4 together with recommendations for future research. Lastly, a conclusion on the findings is drawn in section 5.

2. Materials and Methods

A HD is designed and subsequently tested on its technical performance and evaluated with both healthy subjects and patients with PD in a VE. The following sections elaborate on the design of the HD and on the experimental setups that are used to evaluate both the technical and applied user-performance.

2.1. Design

2.1.1. Position tracking

The VRFree Glove from Sensoryx [31] is used as the basis for the HD. The VRFree is a glove that allows for plug and play ease of use and is highly wearable as it is ungrounded and wireless. The VRFree consists of two gloves that can render the hands very realistically in the VE, because they track the orientation and position of the hands and almost all of the individual phalanges through the use of 11 Inertial Measurement Unit (IMU)s per glove. Next to that, no occlusion of the finger data occurs when the hands overlap due to the use of the IMUs, creating a consistent rendering without the use of external cameras. This achieves a high realism which is an important asset during dexterity rehabilitation, as it allows for precise manual actions similar to how it would be during ADL and position data can be extracted and used for evaluation. The sensory data from the gloves is used as input for the VTF. An Oculus Quest 2 is used as Head Mounted Display (HMD).

2.1.2. Haptics

The implementation of VTF is done through the use of LRA's. This type of actuators consist of a mass that moves in one axis pushed by a coil and a spring. Most VR gloves that implement VTF in a similar way, make use of Eccentric Rotating Mass (ERM) actuators [32], [33]. Compared to ERM actuators, LRAs have lower power consumption during buzzing

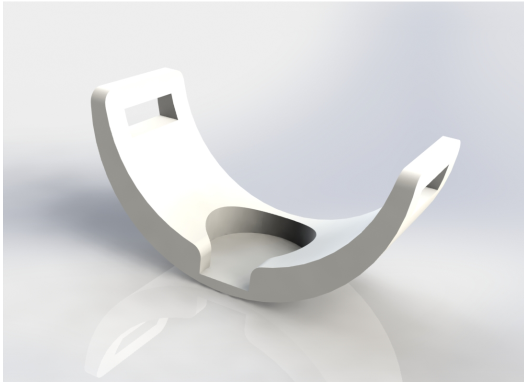

Figure 1. 3D model of actuator socket

and lower latency of 3.38 μAh versus 11.4 μAh and 25ms versus 50ms respectively [34]. ERM actuators work in a relatively wide frequency range, but the amplitude and frequency are dependent. In contrast, LRAs work in a narrow frequency range around their resonance frequency of around 240 Hz, but the amplitude can easily modified through Pulse Width Modulation (PWM). Therefore, LRAs offer a good solution to implement VTF. The actuators are connected to DRV2605L haptic drivers from Texas Instruments [35]. These drivers are designed to be used with vibration actuators to create haptic effects. For LRA's there is auto-resonance tracking that tracks the resonance frequency of the LRA, which is around 240 hz for the used actuators, by constantly monitoring the back-Electro Motive Force (EMF). This optimal operating frequency is influenced by many factors and can change during use. However, due to the resonance tracking, the actuator can be driven at consistent intensities. Next to the resonance tracking, level-calibration is added to compensate for variations in actuator output. After calibration, a 100% signal input will supply the rated voltage to the actuator at steady state, making the haptic output consistent for each actuator. To control multiple haptic drivers and actuators through I2C communication, a micro controller that can communicate with multiple slaves is needed. For this, as combination of a Joy-it MEGA micro controller with a TCA9548A 1-to-8 I2C multiplexer is added to control multiple slave drivers over the single Serial Clock Pin (SCL) and Serial Data Pin (SDA) of the Joy-it MEGA. To minimize interference with the magnetometers of the VRFree glove, both the actuators, the wires, the drivers and the micro-controller are placed on the volar side of the hand and wrist in contrast to the sensors, wires and wrist-module of the VRFRee glove that are located on the dorsal side.

With input of PD patients, it is decided that the fingertips would be the most logic position to locate the actuators as those are the main locations that touch with objects during a grasp and would thus feel most realistic. With one actuator per fingertip, a total of five actuators is used. To ensure the haptic feedback gets conveyed properly to the users' fingertips and are not restricting any movement, a 3D printed fingertip part is designed, as shown in Figure 1, ensuring that the actuators fit snugly inside the glove. Different sizes are built, intended to ultimately be fitted according to each patients' hand size. To store and attach all the hardware to the users' wrist in a wearable and safe manner and without blocking range of motion and interfering with the VRFree, a wrist-case is designed. During a virtual grasp, the VTF is conveyed only for a short moment at the beginning of a touch event in all fingertips, in order to not over-stimulate the receptors and create an irritating feeling. Also, the intensity of the feedback can be varied according to the users' preferences, complying with the patient-tailored rehabilitation.

The Arduino IDE and the Unity 3D Engine are used to program and build the software of the HD, using programming languages C++ and C# respectively. In Arduino the communication to the haptic drivers and, successively, the LRA actuators is build together with a serial communication through the serial port and data retrieval of the accelerometer. In Unity, the VE and haptic detection is built.

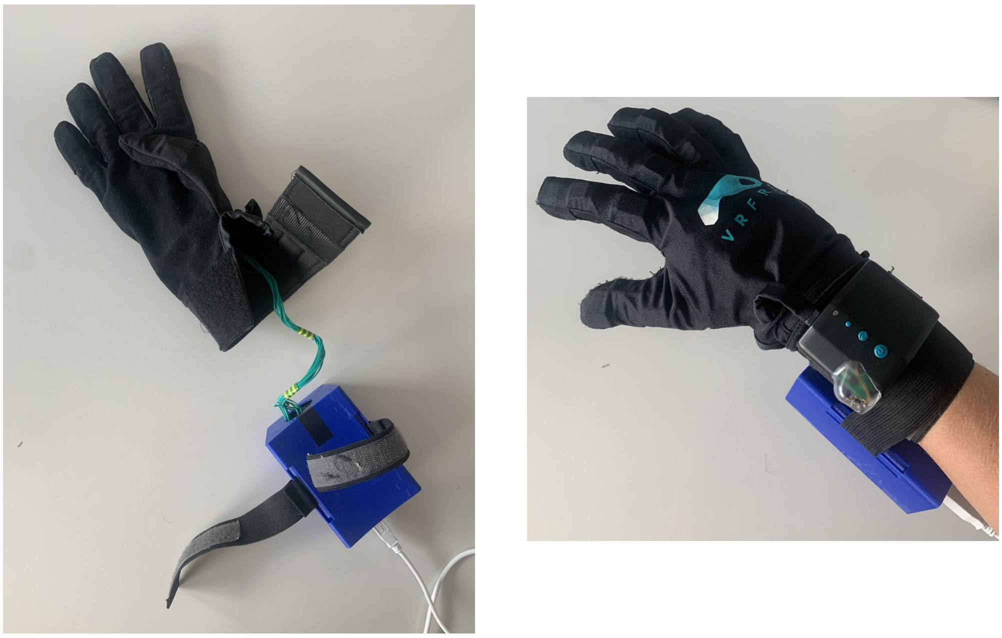

Figure 2. Left: Overview of the system (VRFree glove and HD), right: user wearing the system

2.2. Performance Evaluation

To evaluate the overall performance of the system, both technical tests as well as user tests are performed.

2.2.1. Technical Tests

A series of tests are performed to evaluate technical requirements that regard the latency of the VTF, the intensities of the different feedback modes and the compatibility of the HD with the VRFree Gloves.

Latency. For haptic feedback to be perceived by a user without noticeable timing difference of the corresponding visual feedback, it cannot have a latency, i.e. delay in information, of more than 50ms [36]. To measure the latency between the start of a haptic signal and the actual vibration, a LIS3DH Triple-Axis accelerometer is installed on one of the actuators. A haptic start signal is send to the micro-controller after which the actuator starts vibrating. The acceleration of the actuator is sensed by the accelerometer and then transferred through a serial communicator (hterm) and visualized using MATLAB.

Intensity. To measure whether or not the device is able to convey different intensities of vibrations, the same setup is used as during the latency test. Eight different intensities, labelled 2 to 9, are chosen within the spectrum of vibrations that the patients were able to perceive during preliminary tests. These eight intensities are scaled proportionally to the input value for the haptic controller. To see whether a linear correlation exists, the average peak acceleration values for each intensity are extracted from the data and plotted against the intensity values using MATLAB.

Compatibility. Due to magnetic interference induced by currents or the vibrations coming from the actuators, the IMUs from the VRFree could be disturbed. To evaluate if the designed HD is compatible with the VRFree glove, a visual comparison is made by the researcher between the virtual rendering of the hands both with VTF and without to determine if no visually noticeable disturbances occur, ie. the visual perception of the movements and rendering of the hands is similar with and without feedback. This is done in a VE environment where only the hands are present.

2.2.2. User Tests

The user tests examine the addition of VTF compared to no-feedback in VR by evaluating the grasp performance, followed by a questionnaire to asses the HX, usability and value of the HD in general. The complete system with VRFree gloves and the HD is tested with both healthy users and users with PD with a dexterity task in a newly designed VR setup.

Participants. Five patients (three female) with an average age of 63.8 +- 11.3 and in PD stage 1 to 3 were involved in this test. All of them are right-handed and for three of the patients the right-hand was also the affected hand. Six healthy subjects (three female) with an average age of 63.3 +- 11 and with no reported deficiencies participated in manual dexterity tasks. All of them are right handed. The participants signed informed consent forms. All of them were informed about the purpose of the experiment, were able to discontinue participation at any time, and no payment was provided for the participation.

VR test setup. For the grasping tests, a simple VR scene is built in Unity software where the user has to grasp a virtual egg in a neutral environment. This specific setup mimics a realistic rehabilitation setup where patients practice the handling of a delicate object that they could encounter in ADL and where they have to control their forces in order to not break or damage the object. This is a great example of a manual dexterity task in ADL. The scene is designed with only essential components, so that the task is very self-explanatory and can be full-filled without any extra instructions during the test. This should also ensure full engagement and focus of the users during the task. The layout of the scene is shown in Figure 3. The grasp test is set up as follows: An egg appears at a random location on the table. The users grasps the egg with their affected-side hand or, if not applicable, with their preferred hand, and hold it for three seconds without applying too much virtual force, i.e. without closing the fingers too much and penetrating and consequently "breaking" the virtual egg. When the user succeeds in grasping the virtual egg, the grasps is marked as completed. If the user applies too much virtual force to the egg or it falls off the table, the grasp is marked as failed.

VR test execution. Each user is asked to wear the complete system with two gloves and the HD attached to the objective hand. Help is provided with putting on the HMD, VRFree gloves and HD. Prior to the virtual test, the finger positions are calibrated with the VRFree "Hand pose Calibration" procedure and the users are asked to perform some grasps using a real egg. During these grasps, the finger positions are used as the base value below which they are penetrating the virtual egg too much which leads to a bad grasp. Then, the user performs several practice grasps in the VR scene without haptic feedback until they feel familiar enough with the VE and the system. The user is asked to choose a vibration intensity that is most comfortable for them. After this practise, the actual test starts. The user grasps the virtual egg 10 times with haptic feedback, then 10 times without, followed by another 10 times with feedback. After the tests, the user takes off the HMD, gloves and HD and is asked to fill in the questionnaire.

VR test data analysis. There exists no universal smoothness parameter for grasping performance in a VE, so to determine and compare the performance, several characteristics of the grasps are calculated from the collected data. For this study grasp performance is measured through motion smoothness, grasp completion time and accuracy. *Grasp smoothness* is determined through the average jerk during the grasp trajectory, which starts when the egg appears and stops three seconds before the grasp is completed [37], [38], [39]. The jerk is the change of acceleration per unit time and is calculated by taking the third derivative of the position. The position data is linearly interpolated to create uniform samples [40] and then filtered and smoothed using a Savitsky-Golay filter to reduce noise but keep the tendency of the data. *Grasp completion time* is calculated as the time between the moment the egg appearances until the grasp is completed and the egg disappears. *Grasp accuracy* is determined through the total amount of good grasps during the total of 10 grasps. To calculate these characteristics, during the virtual grasps data on the position of the wrist, distance of the fingers with respect to the thumb, the egg appearance time,

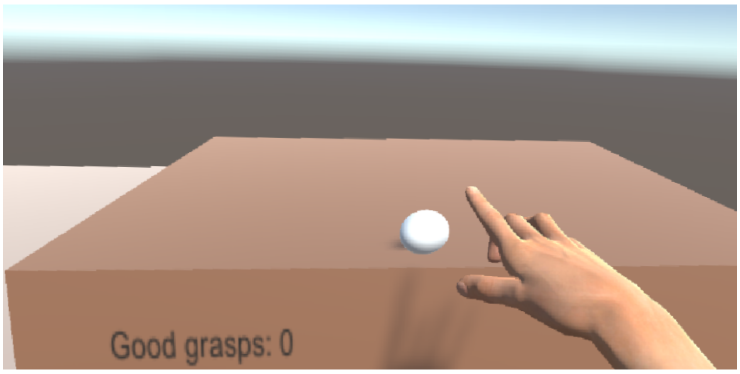

Figure 3. Grasping scene in VR

grasp completion time and the amount of good and bad grasps are collected. This data is collected in .csv files and evaluated through the use of MATLAB.

Questionnaires. A questionnaire is used to subjectively asses both the HX and the usability of the designed system. This is important for the evaluation of the HD, as it provides direct feedback from the users and their experience with the VTF and compliance with the system. The questionnaire can be found in German in Appendix A. Suitable questions regarding the haptic feedback from the HX questionnaire are adopted [41] as well as questions from the USEQ and custom questions regarding the grasping. The questions from the HX questionnaire are categorized into autotelic, immersion, realism and harmony. Autotelic refers to the purpose of the device, immersions is focuses on the engagement, focus and involvement in the VR tasks. Realism is aimed at the realism of the haptic feedback, in the sense that it convinces the user that it has touched an object. Harmony is related to in what extent the VTF felt connected to the task and is appropriately timed. The general questions about the VTF of the designed HD specifically contain the comfort of the intensities, to what extent the grasp was easier with or without the feedback and whether or not the confidence during the grasp increased. The USEQ questions gather feedback on the enjoyment or discomfort during the use of the system together with a rehabilitation focused question. A 5-point Likert Scale is used in which each item is scored from 1 (strongly disagree) to 5 (strongly agree) to quantitatively gather the results. To evaluate the usability, the SUS questionnaire is also included and uses the same scale. The SUS is a well validated usability scale taking the effectiveness, satisfaction and efficiency of the tested system into account through 10 similarly weighted items. From the results, a SUS score in the range of 0% to a 100% is calculated of which a score of 70% to 100% represents acceptable to excellent usability [42].

3. Results

This section contains the results of the technical and user tests that are performed on the HD as described in section 2.

3.1. Technical Tests

3.1.1. Latency

Figure 4 shows the acceleration of a LRA during subsequent collision signals. When zooming in, Figure 5 shows the acceleration when a collision signal is started and Figure 6 shows the acceleration when a collision is stopped. An average latency of 13 +- 12 *ms* of the acceleration as a consequence of the collision start signal is found. A latency of 38.75 +- 6.25 *ms* is found when the collision is stopped.

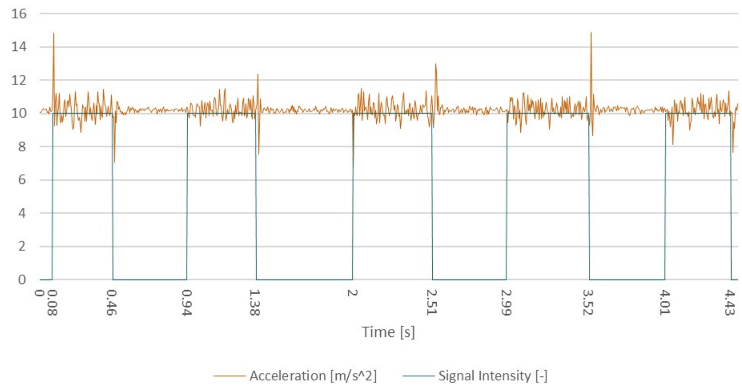

Figure 4. Acceleration of LRA on collision signals

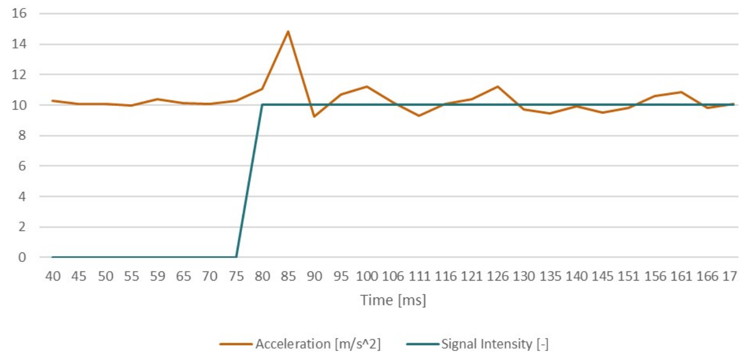

Figure 5. Acceleration of LRA on collision start signal

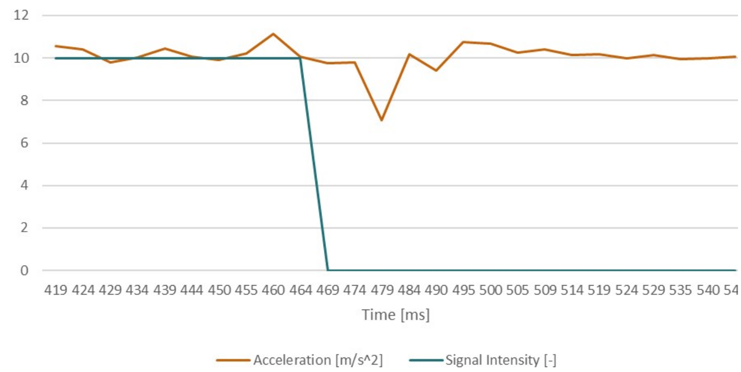

Figure 6. Acceleration of LRA on collision stop signal

3.1.2. Intensity

Figure 7 shows the acceleration of a LRA when the different intensities from 2 to 9 are set. The average peak values are displayed against the different intensities in Figure 8 together with a linear relationship between the lowest and highest peak values as a reference.

3.1.3. Compatibility with VRFree

The rendering of the hands in a VE when the HD conveys feedback is visually evaluated and compared to when the HD does not convey feedback. No visually noticeable disturbances are found between the two conditions.

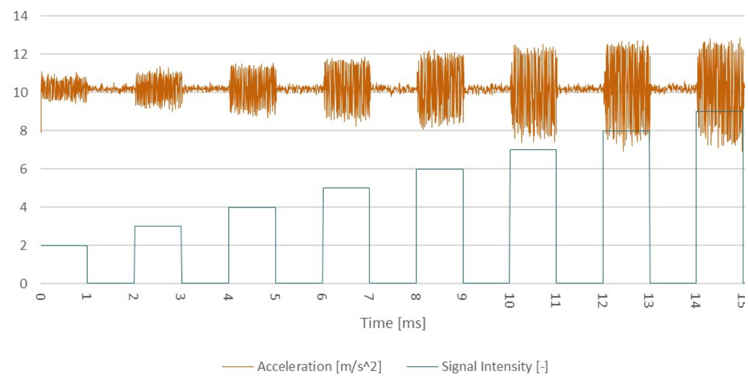

Figure 7. Acceleration of LRA during different intensity settings

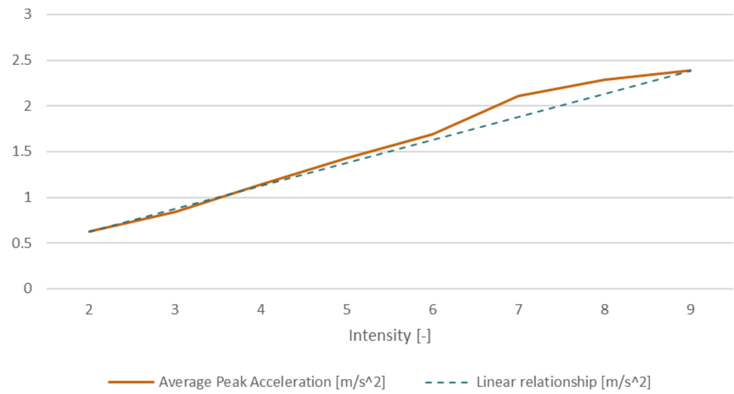

Figure 8. Average peak-acceleration of LRA during different intensity settings

3.2. *User Tests*

3.2.1. VR test

During the VR test with patients 1 to 4, the sensing mechanism of the gloves was not performing as required, causing inaccurate rendering of the hand in the VE. Consequently, the patients had to either use the non-affected, non-preferred hand or had a unrepresentative representation of their hand in the VE, making the grasping more difficult and creating incomparable data. Patient 5 and healthy subjects 1 to 6 did have properly working gloves. Thus, only the numerical data of healthy subjects 1 through 6 and patient 5 is used. To facilitate data comparison, a Haptic Factor (HF), shown in Equation 1, is introduced. This describes the ratio of a measured characteristic where haptic feedback was applied, T, to the no feedback condition, NH. A factor of unity means they were similar.

$$HF = \frac{T}{NH} \tag{1}$$

Figure 9 shows a bar graph in which the HF of the average completion times are shown.

Figure 10 shows a bar graph in which the HF of the average completion times per travelled distance from the starting position of the wrist to the egg at the beginning of the grasp is shown.

Figure 11 shows a bar graph in which the HF of the average amount of good grasps out of ten total grasps is shown.

Figure Figure 12 shows a bar graph in which the HF of the average jerks are shown.

3.2.2. Questionnaires

The results from the questionnaires are shown through the use of bar graphs that show the average Likert Scale-based scores together with the maximum and minimum scores for

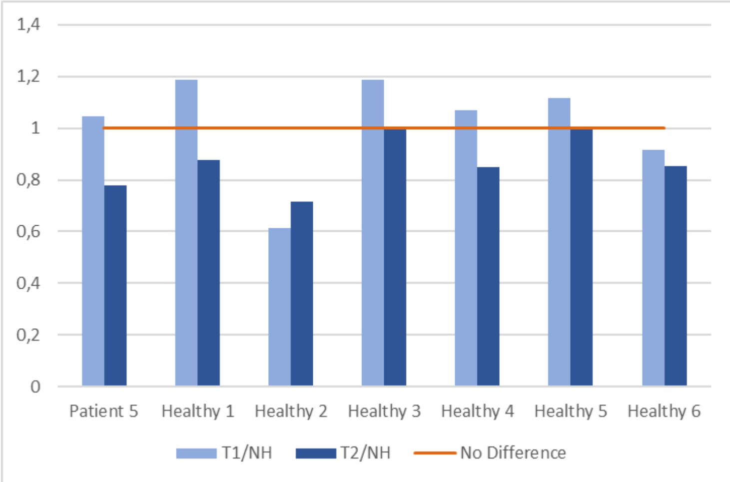

Figure 9. HF of average completion times

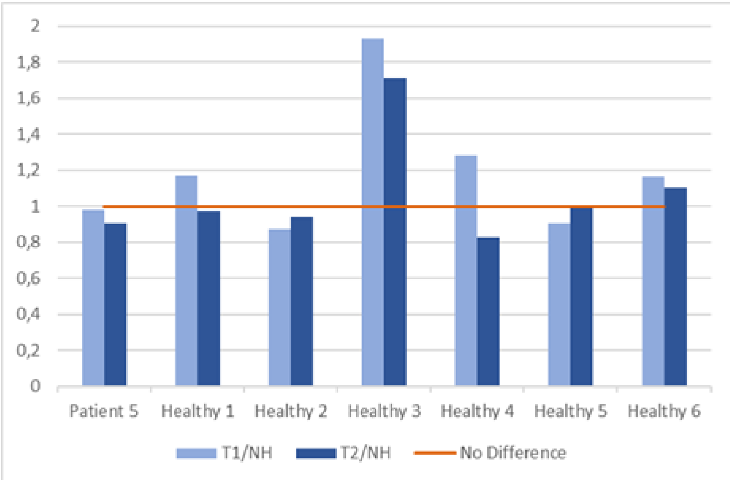

Figure 10. HF of average completion times per travelled distance

both PD patients and healthy subjects. Figure 13 shows the SUS scores with an average of 73.5 for patients, 76.25 for healthy subjects and 74.88 for all subjects. Figure 14 shows the scores for the four HX categories. Figure 15 shows the scores for the task related questions of the questionnaire and Figure 16 shows the scores for the modified USEQ questionnaire.

4. Discussion

4.1. Technical Testing

As mentioned in subsubsection 2.2.1, the latency of the haptic feedback should not exceed 50 ms for the delay to be imperceptible. Both at the beginning and the end of a haptic event, a latency lower than this threshold is found, meaning that the perception of the feedback should be simultaneous with the visual feedback and create a realistic feedback timing-wise. A higher latency is found for stopping the actuator compared to starting it, which might be due to the inertia of the moving mass within the LRA's. As the haptic feedback is only conveyed as a short signal at the start of a touch event, the delay when shutting the actuator down is not of high importance. The main delay in latency is assumed to be coming from the serial communication between the Unity software, the micro-controller and the serial communicator consecutively together with the primary delay of the actuator itself. The found latency is in-line with a similar haptic VR glove system that utilized LRAs designed by [33], where a latency of 25ms is found.

A linear relationship is found between the intensity settings of the HD and the acceleration of the actuators for the intensities between 2 and 6. At intensities 7 and 8, the

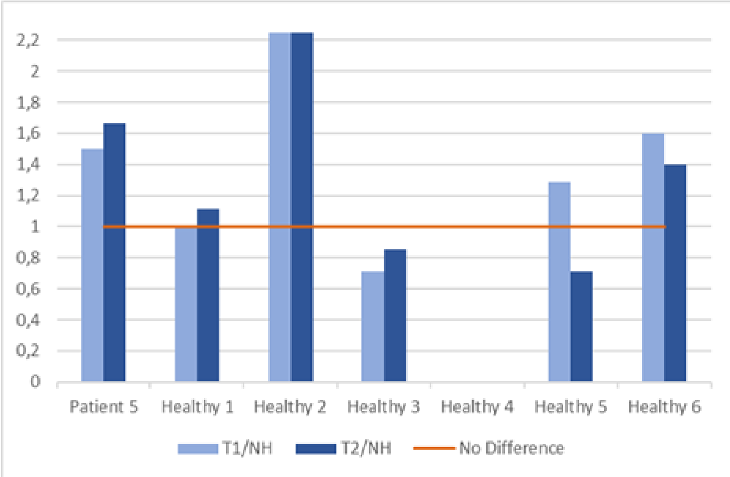

Figure 11. HF of amount of good grasps

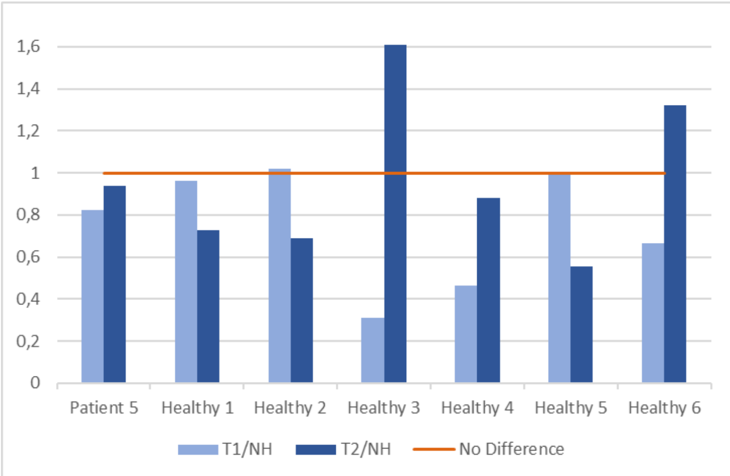

Figure 12. HF of average jerk

acceleration shows some non-linear values with a deviation of 12% and 7%, respectively, compared to a linear relationship between the minimum and maximum acceleration values at intensities 2 and 9. This may lead to relatively higher perceived intensities at these settings, but should not make a significant impact on the use of the HD as the user is able to choose an intensity setting that suits them best.

During the compatibility tests, no visually noticeable disturbances in rendering of the hands is found with or without the VTF activated. From this we can assume that the possible interference of the HD does not affect the visual representation of the hands and their use in a VE. As this is only a visual test, no quantitative data on possible errors is available. For more in depth compatibility testing it would be interesting to look at the actual position data from the VRFree glove and compare it with data from an optical sensor as reference both with and without VTF. However, a visual evaluation seems sufficient for the current purpose.

As far as the technical aspects of the device, the results suggest that the HD performs adequate for use. Next to fulfilling technical requirements, the HD needs to accomplish the expected goals in terms of performance enhancement in VR rehabilitation.

4.2. User Testing

Numerical data during the VR tests and subjective data from the questionnaires is collected. As the sensors did not work properly during most of the tests with patients, only

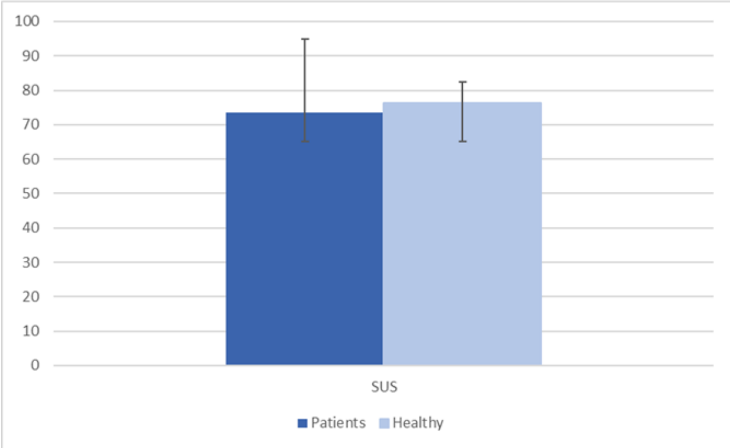

Figure 13. SUS scores

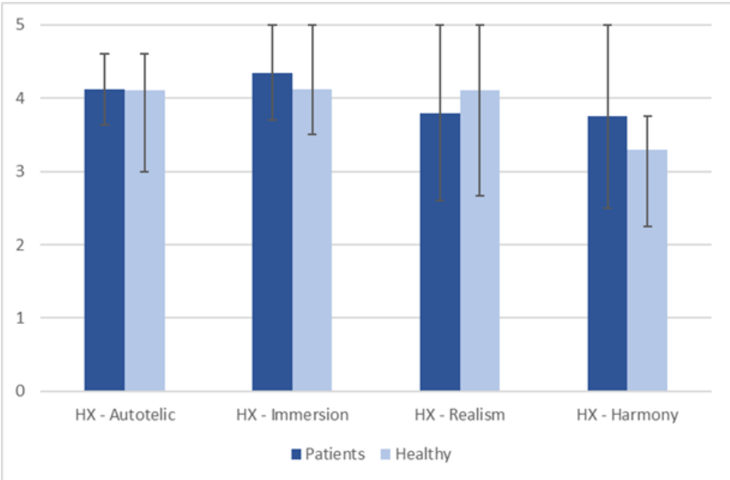

Figure 14. Scores of four categories from the HX questionnaire based on a 5-point Likert scale

data from one female with PD is used. The questions from the questionnaires that did not specifically involve the grasping are assumed to be valid and thus are all used.

From the numerical data, a clear trend is found in the ratio of the completion time per grasp with respect to the condition without haptic feedback. During the second session with haptic feedback almost all subjects have lower completion times with respect to the no feedback condition. This might be due to the fact that during the first session the users still had to get used to the haptic feedback and with the second session they had more experience with the haptic feedback, making the grasping easier. Difficult here is the influence of training that occurs during the sessions in a row. Even though the users were able to get familiar with the device and practice the grasps without feedback before hand, there might always be the influence of training involved. Testing in a random order of feedback conditions might resolve this uncertainty. When evaluating the completion time per travelled distance, some improvement with the VTF is found in five of the subjects, including the patient. Here, no clear trend between the first haptic session compared to the second is found, which could argue against a learning curve. This measure is perhaps more valuable as it takes the length of the trajectory into account which was different for each grasp due to randomization. However, for relatively short distances, this could magnify the neurological processing time needed for starting a grasping movement, and thus give more negative results. The accuracy in terms of good grasps per a total of ten grasps, seemed improved in three of the subjects, including the patients, which could indicate that the patient has benefited from the feedback. In the other three subjects there was no clear improvement. From this, no clear trend can be found and would suggest that the users

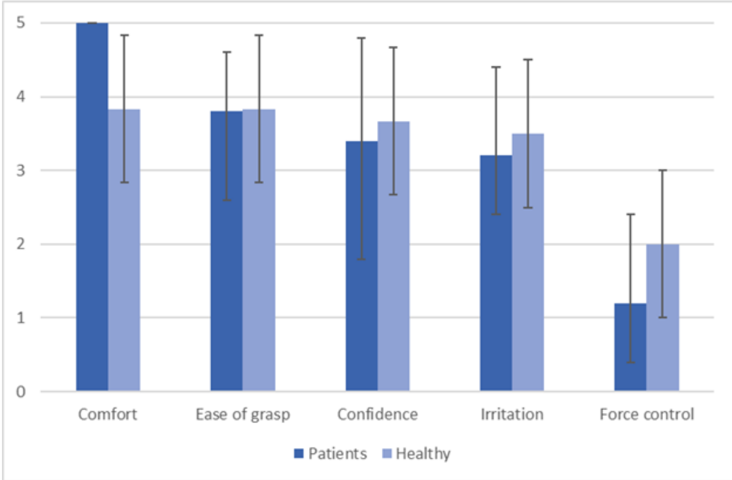

Figure 15. Scores of task-related questions based on a 5-point Likert scale

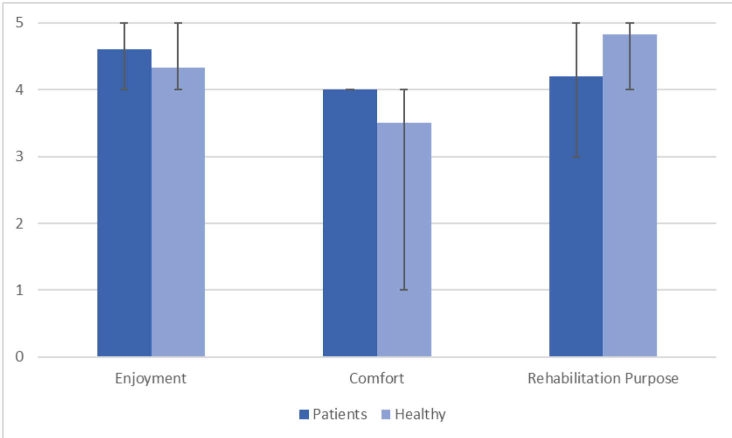

Figure 16. Scores of three questions of the USEQ based on a 5-point Likert scale

need to have more detailed feedback during the grasp. The data of healthy subject 4 was inaccurate due to problems in the calibration of finger distance for marking a bad grasp and is left out. In almost all subjects there seems to be an improvement in the average jerk during the grasp trajectory. This indicates that in terms of smoothness, the grasping improved due to the feedback providing the subjects with higher confidence in moving to and grasping the objects. However, the position data had to be differentiated three times, in order to retrieve the jerk. This lead to the noise in the data becoming larger every iteration. To reduce noise and retrieve a smoother signal, a digital filter was applied to the position data. To calculate a more adequate average jerk, it would have been better to save the acceleration data of the IMUs during the user tests as well. Also, including other smoothness measures such as spectral arc length or normalized jerk would have been interesting to compare. Looking at all the discussed grasp performance characteristics, it seems that in terms of jerk and total completion time some improvement is visible. In accuracy and completion time per distance there is no clear trend. Interestingly, in all characteristics, the patient seemed to show improvement with the VTF. However, it is difficult to make any harsh statements on this data from the small group.

As for the subjective data, the scores from the HX questions are subdivided according to the four categories; autotelic, immersion, realism and harmony. All of the categories score above 3 for both patients and healthy users, which means that on average the HD the haptic feedback can be assumed as proper. For both immersion and harmony the patients rated the device higher than the healthy user, but for realism it was rated higher by the healthy users. This could be due to the fact that the patients experienced more supporting effect of the haptic feedback compared to the healthy users and therefore felt that they could better perform the grasp and were more immersed into the task. As the feedback only consists of vibrations, it would be understandable that the device would not score as high in terms of realism. However, it is rated higher than the harmony, which is unexpected. As the positive harmony question regarding the appropriateness of the location and the feedback gets a high score in general, it suggests that the other questions which were asked from a negative perspective, might have been misinterpreted, leading to a lower average score. Another study with a glove system that utilizes VTF, shows similar results in terms of realism [32], indicating that the found results on realism are valid.

The scores of the USEQ questionnaire show that all questions score above 3 on average. It is positive that the patients seemed to enjoy the device and did not feel discomfort during use. Interestingly, the rehabilitation purpose is acknowledged more by healthy users than patients, which could have to do with the fact that for healthy users it is difficult to estimate the impact of such a device on rehabilitation but are enthusiastic about the technological advancement.

From the numerical data it showed that the grasping time improved with the haptic feedback during the second session with feedback, which is in-line with the scores on the question about the ease of grasping with the haptic feedback. In contrast, most subjects did not feel a big difference in managing the grasp with or without feedback, which is in-line with the results from the grasp accuracy.

The SUS scored an average of 73.5 for patients and 76.25 for healthy subjects, which are both above the 70, from which a systems usability is acceptable [42]. This can be assumed to be a valid outcome as it shows that the users did not give the device a high usability score, which would be unreasonable due to being a prototype. When compared to a study that evaluated a haptic controller in PD an improvement is found in the present system in terms of usability. The haptic controller system resulted in an average SUS score of 70, but with minimum score of 47.5 [30], which was mostly due to a limited field of view and difficulties in tracking connection and thus leaving room for improvement. The present study was able to use a HMD and finger tracking with the VRFree to eliminate these problems and at the same time target the implementation into VR rehabilitation. The minimum scores of the present study are 65 for both patients and healthy subjects. These are below the average and suggest that the current state of the device should be further developed in order to be implemented into rehabilitation. Mostly, the users stated that they would need technical support during the use of the device. This can be due to the fact that the total device consists of a HMD, two gloves and the HD around their wrist which still had to be connected to the laptop through cables in a specific manner. The simplicity of the dexterity task in the newly designed VE might play an important role in the usability of the system and is something that is interesting for further rehabilitation research for PD patients. In the VE no extra impulses or elements were implemented, so that the patients were able to fully focus and engage in the task. As it was very self-explanatory, it mimics real life situations in which patients have to make cognitive decisions based on what they see. Also, no notions of impaired movement freedom of the fingers was reported as a result of the actuators on the fingertips. This is in contrast with a study that suggested that actuators on the fingertips would impede finger movement [43], but shows the usability of the designed 3D finger parts.

Some general feedback from the VR tests was about the fitting of the gloves and ensuring that the eggs did not appear too far from the user such that they had to completely extend their arm. Unfortunately, it was difficult to calibrate the VE environment to the same distances for all users, as the tests were mostly performed in different rooms. The HMD sometimes had difficulties to locate its orientation, which made the VE sometimes appear higher, lower or further away than designed and then had to be adjusted accordingly. This also made the comparison of user data more complex as the coordinates of the eggs and hands were not similar for each user. It was also suggested to increase the intensity of the feedback during the grasp, so that the user could know how far they would penetrate

the object. This aligns with the score of the question about force control and the results of grasping accuracy. During the design phase, the option of variable intensity of tactile feedback was tested as it would provide direct feedback to the users during their grasp and would perfectly fit the objective. However, due to the limited tracking sensitivity of the fingers and the differences in hand sizes, the haptic feedback would become disturbing and distracting as the intensities would be constantly changing. Pre-test calibrations on finger distance during grasping were tried, but did not yield the desired accuracy during grasps. Therefore, it was decided to stick to just one pre-defined intensity and only short vibration at the first contact with the object. However, it would be interesting to implement proportional intensities linearly with the penetration distance into future upgrades of the HD. This would be possible if the accuracy and fitting of the gloves has been improved and when more detailed rendering of the hands is implemented into the software.
VTF has been implemented in VR user studies and has shown promising results with object interaction [32], [33]. However, little to no research has been done on VR haptic glove systems in PD, which makes this present study a pioneer in this untouched area and thus provides new insights on the implementation of VTF in VR dexterity rehabilitation in PD. This makes comparison of the current results to the prior research difficult, but sets the first step in implementing haptic feedback into VR rehabilitation in PD. Overall, the patients seem to have a positive opinion on the usability, comfort and addition of the device and seem to perceive and experience the feedback in a similar way. In combination with the positive results on completion time and smoothness, it indicates that the HD in combination with the VR gloves could be a feasible addition to current VR dexterity rehabilitation practices. However, there is clear room for improvement of the device to actually be implemented into rehabilitation.

4.3. Future Recommendations

For the device to actually be implemented into rehabilitation for PD patients, the overall design of the hardware would have to be minimized in terms of size, weight and amount of cables. A custom made Printed Circuit Board (PCB) would improve the size and weight and adding a wireless connection between the micro controller and visual display would already make the device more portable and easier to use without technical support. Also the connection between the actuators and the micro-controller should be integrated into the glove or even made wireless to prevent damage to the cables and to make it easier for the user to put the cloves on. Together with a better fit of the gloves themselves, this would enhance the usability.

Testing with different intensities for different virtual penetration levels would be interesting to provide even more detailed feedback during precision grasps and thus more precise practice of manual dexterity tasks. In order for this to work, the position tracking and rendering of the hands and especially the fingers should be more precise. Also, improvements in the software of the VE could increase the realism and precision of the experience by, for example, better calculations on how the physics in the VE are handled and more detailed collision detection of the individual fingers for individual finger haptic feedback.

Experimenting with both kinaesthetic and tactile feedback would be another interesting step. As the haptic technologies are constantly evolving and many different solutions have already been found for object interaction in VR, a next step would be to make the grasping for PD patients even more realistic by also stimulating the kinaesthetic sense. Currently, the most lightweight and minimalistic way to do so is through the use of artificial tendons. Such systems have already shown their applicability in VR, but not yet in patients or during more precise dexterous manipulations [44] [45]. This might have to do with the force rendering and actuator control challenges these mechanical systems bring. However, with the current interests in haptic feedback and the research on combined sensing and actuation mechanisms, these challenges could be overcome.

Further studies are needed to investigate the effect of VTF in dexterity rehabilitation on the performance of ADL and consequently the QoL of patients. For this, first larger patient groups and perhaps also patients in further stages of the disease should be tested with the system during the designed VR dexterity task. Later on, the system can be integrated into rehabilitation programs with multiple different ADL tasks to eventually evaluate the effect on QoL during a randomized clinical trial.

5. Conclusions

A novel haptic system, that for the first time extends the VRFree gloves with VTF on the fingertips by means of a newly designed HD, is evaluated for its usability in PD VR rehabilitation focused on dexterous ADL.

Technical tests yielded positive results in terms of latency, intensities and it showed that the HD produces no visually noticed interference with the VRFree gloves.

User experiments were conducted in which the addition of VTF upon virtual touch was compared to no-feedback during a dexterity task in a newly designed VE. The VE ensured high engagement and focus of the subjects due to its self explanatory setup. The tests revealed positive results on increased grasp performance in terms of grasp time and smoothness with the VTF among healthy subjects. The patients seemed to perceive the VTF in a similar way as the healthy subjects. A good HX evaluation and an average SUS score of 75 was found among all subjects.

Despite the small test group, the results of this study demonstrate the usability of VTF in PD VR rehabilitation by testing a novel combination of the VRFRee gloves and a newly designed HD that integrates VTF on the finertips. Therefor, VTF is a promising addition to current VR rehabilitation focused on improving dexterity during ADL in PD.

To further increase usability of the system and to eventually be implemented into rehabilitation, the system should be improved by decreasing technical difficulty, by providing more precise tracking and rendering for implementation of more detailed feedback during grasps. Further studies will be needed to validate the value of the system as a rehabilitation tool to improve QoL in PD.

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

Data Availability Statement: The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Acknowledgments: We are very grateful for all the subjects that participated in this studies. We would also like to thank Rolf Adelsberger and the Sensoryx team for providing technical support of the VRFree glove and insigts on software infrastructure, ARTORG lab members for providing electronics and technical support and Erwin van Wegen for professional knowledge on PD

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Conflicts of Interest: "The authors declare no conflict of interest".

Acronyms

ADL Activities of Daily Living

AR Augmented Reality

DBS Deep Brain Stimulation

EMF Electro Motive Force

ERM Eccentric Rotating Mass

HD Haptic Device

HF Haptic Factor

HMD Head Mounted Display

HX Haptic Experience

IMU Inertial Measurement Unit
LRA Linear Resonant Actuators
PCB Printed Circuit Board
PD Parkinson's Disease
PWM Pulse Width Modulation
QoL Quality of Life
SCL Serial Clock Pin
SDA Serial Data Pin
SUS System Usability Scale
USEQ User Satisfaction Evaluation Questionnaire
VE Virtual Environment
VR Virtual Reality
VTF Vibrotactile Feedback

Appendix A

Fragen speziell zum haptischen Feedback

Haptisches Feedback bezieht sich auf alles, was Sie mit dem Tastsinn fühlen. Es können Vibra- 579
tionen, Kraft, Temperatur, Druck oder jede andere körperliche Empfindung sein [1]. Während des Tests erlebten Sie Vibrationen als haptisches Feedback als Hinweis auf den Beginn eines Berührungsereignisses. Dieses Vibrationsgefühl ist das haptische Feedback, auf das wir uns in den folgenden Fragen beziehen.

		Lehne völlig ab				Stimme völlig zu
1.	Das haptische Feedback war zufriedenstellend	1	2	3	4	5
2.	Mir gefällt, wie sich das haptische Feedback selbst anfühlt, unabhängig von seiner Rolle im System	1	2	3	4	5
3.	Ich mochte das haptische Feedback nicht	1	2	3	4	5
4.	Ich würde das System ohne das haptische Feedback bevorzugen	1	2	3	4	5
5.	Ich mag es, das haptische Feedback als Teil des Erlebnisses zu haben	1	2	3	4	5
6.	Ich fühlte mich aufgrund des haptischen Feedbacks mit dem System verbunden	1	2	3	4	5
7.	Das haptische Feedback half mir, mich auf die Aufgabe zu konzentrieren	1	2	3	4	5
8.	Das haptische Feedback verstärkte meine Beteiligung an der Aufgabe	1	2	3	4	5
9.	Das haptische Feedback hilft mir zu unterscheiden, was los war	1	2	3	4	5
10.	Das haptische Feedback war realistisch	1	2	3	4	5
11.	Das haptische Feedback war glaubwürdig	1	2	3	4	5
12.	Das haptische Feedback war überzeugend	1	2	3	4	5
13.	Das haptische Feedback fühlte sich vom Rest der Erfahrung abgekoppelt an	1	2	3	4	5
14.	Das haptische Feedback fühlte sich angemessen an, wann und wo ich es fühlte	1	2	3	4	5
15.	Das haptische Feedback fühlte sich fehl am Platz an	1	2	3	4	5
16.	Das haptische Feedback lenkte mich von der Aufgabe ab	1	2	3	4	5
17.	Das haptische Feedback hatte eine angenehme Intensität	1	2	3	4	5
18.	Das haptische Feedback erleichterte das Greifen	1	2	3	4	5
19.	Das haptische Feedback hat mich beim virtuellen Greifen sicherer gemacht	1	2	3	4	5
20.	Das haptische Feedback war irritierend	1	2	3	4	5
21.	Das haptische Feedback machte es nicht einfacher, meine Greifkraft zu kontrollieren	1	2	3	4	5

[1] Sathiyamurthy, 2020.

Fragen zum Gesamtsystem

Mit *dem System* meinen wir Folgendes: Der Handschuhe mit vibrierendem haptischem Feedback, die für die Rehabilitation in der virtuellen Realität verwendet werden könnte.

		Lehne völlig ab				**Stimme völlig zu**
22.	Ich denke, ich würde das System regelmäßig nutzen	1	2	3	4	5
23.	Das System erscheint mir unnötig kompliziert	1	2	3	4	5
24.	Ich finde, das System ist einfach zu benutzen	1	2	3	4	5
25.	Ich denke, ich bräuchte technische Unter- stützung um das System nutzen zu können	1	2	3	4	5
26.	Ich finde, dass die verschiedenen Funktionen das System gut integriert sind	1	2	3	4	5
27.	Das System erscheint mir zu uneinheitlich	1	2	3	4	5
28.	Ich glaube, dass die meisten Leute die Benutzung das System schnell erlernen können	1	2	3	4	5
29.	Das System erscheint mir sehr umständlich zu benutzen	1	2	3	4	5
30.	Ich fühle mich bei der Benutzung das System sehr sicher	1	2	3	4	5
31.	Ich musste einiges lernen, um mit das System zurecht zu kommen	1	2	3	4	5

		Gar nicht				**Sehr viel**
32.	Wie sehr schien Ihre Erfahrung in der virtuellen Umgebung mit Ihrer Erfahrung in der realen Welt übereinzustimmen?	1	2	3	4	5
33.	Hat Ihnen Ihre Erfahrung mit dem System gefallen?	1	2	3	4	5
34.	Haben Sie sich während Ihrer Erfahrung mit dem System unwohl gefühlt?	1	2	3	4	5
35.	Glauben Sie, dass dieses System für Ihre Rehabilitation hilfreich sein wird?	1	2	3	4	5

36. Haben Sie Empfehlungen zur Verbesserung des haptischen Feedbacks während der Virtual-Reality-Rehabilitation?

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