

Enhancing Therapist Capabilities in Robotic Therapy through Haptic Feedback and Immersive Virtual Reality: An Experimental Study

An Experimental Study

by

Matti Lang

Student Name	Student Number
Matti Lang	5632935

Supervisors:
Laura Marchal-Crespo
Alexandre Ratschat
Alex van den Berg

Thursday 6th June, 2024

Preface

Robotic therapy for neurorehabilitation patients has been shown to improve treatment outcomes in comparison to conventional therapy. However, these systems are often heavy, bulky and do not provide a straightforward method for the therapist to interact with the exoskeleton. In this thesis we present a novel telerehabilitation system with therapist-in-the-loop combining haptic feedback with immersive virtual reality (IVR). We conducted an experiment to test this teleoperation system, where participants in pairs had to communicate an arm pose related to an activity of daily living (ADL). The results indicate that the teleoperation system allows the therapist to interact with the exoskeleton efficiently and adjust arm movements rapidly. However, we also found that the patient could lose some motivation in this system due to the therapist taking over some of the movements from the patient. In the future this system could also be tested with the patient also immersed in VR as this has been shown to increase motivation.

This Master's Thesis is submitted as one of the requirements for the Master Robotics at the Mechanical Engineering Faculty at the University of Technology, Delft. The presented research was supervised by Dr. Ing. L. Marchal Crespo, Alex van den Berg, and Alex Ratschat, in the Department of Cognitive Robotics in the MLN Lab. All project codes can be found on the Delft University of Technology Gitlab:

Teleoperation Controller: gitlab.tudelft.nl

Simulink Control: gitlab.tudelft.nl

Unity Visualization: gitlab.tudelft.nl

All data and code for processing data can be found at the Project Storage of Delft University of Technology:

`tudelft.net\staff-umbrella\Telerehabilitation Experimental Study`

Matti Lang
Delft, June 2024

Acknowledgements

First I would like to thank my supervisors Laura Marchal-Crespo, Alex van den Berg and Alex Ratschat. Alex & Alex, I really enjoyed our weekly meetings! Your advice and tips helped me get through this project and your positive spirits and humor made me enjoy the journey. Thank you Laura for the overall supervision of my project and the invaluable expertise you provided on my thesis, it would not have been possible without you. I also want to thank the clinical expert from Erasmus MC for trying out the teleoperation system and giving me feedback and tips. I also want to thank all the participants of my experiment and all the members of the MLN Lab - it felt like a small family! Finally, I want to thank all my friends and family for their support throughout my studies. I could have never done any of this without them.

Contents

Preface	i
Acknowledgements	ii
1 Scientific Paper	1
A Statistical Analysis	18
A.1 Total Time	18
A.2 Path Length	19
A.3 SPARC	21
A.4 Questionnaire Data	23
A.4.1 Mean and Standard Deviation	23
A.4.2 Workload (RTLX)	24
A.4.3 Usability (SUS)	30
A.4.4 Motivation (IMI)	32
B Experiment	34
B.1 Experimental Procedure	34
B.2 Poses	35
B.2.1 Base Position	35
C VR Environment	36
C.0.1 Digital clone ARMin	36
C.0.2 VR arm	37
C.0.3 Female and Male torso	38
C.0.4 Experiment	40
C.0.5 UXF	41
D Simulink	42
D.0.1 Scope Board	42
D.0.2 ARMin Control	43
D.0.3 Arm Weight Compensation	45
E Informed Consent Form	46
F Qualtrics Survey	52

1

Scientific Paper

DELFT UNIVERSITY OF TECHNOLOGY

RO MSc THESIS

RO57035

**Enhancing Therapist Capabilities in Robotic
Therapy through Haptic Feedback and Immersive
Virtual Reality: An Experimental Study**

Author:

Matti Lang (5632935)

Supervisors:

Alex van den Berg a.vandenberg-2@tudelft.nl

Alexandre Ratschat a.l.ratschat@tudelft.nl

Laura Marchal-Crespo l.marchalcrespo@tudelft.nl

June 6, 2024



Abstract—To offer engaging neurorehabilitation training to stroke patients, robotic exoskeletons have emerged as a beneficial tool to train motor tasks. However, in robotic therapy the therapists are often limited in how they can interact with the patients. The training programs with exoskeletons are often standardized, not allowing the therapist to directly manipulate them and customize the training for specific patient needs. This paper presents a novel telerehabilitation system incorporating a therapist-in-the-loop haptic interface and immersive virtual reality (IVR), aimed at improving the interaction dynamics between patients and therapists during rehabilitation sessions. We conducted a human factors study involving 36 participants grouped in pairs, assigned as "Leaders" or "Followers," where the Leader had to guide the Follower (positioned in the exoskeleton) to a specific arm pose related to activities of daily living (ADL). This task was done under two conditions: demonstration and teleoperation. In the demonstration condition, the Follower could see the Leader displayed on a 2D screen in front of them showing them visually what was the correct pose whereas in the teleoperation condition, there was no visual aid but the Leader could guide the Follower using the haptic device. The study explored the efficiency, workload, and user experience of both modalities. Results indicated that teleoperation significantly reduced the time to complete tasks and facilitated more efficient and smoother movement patterns. While Leaders experienced reduced workload and increased motivation with the teleoperation condition, Followers reported less workload but also decreased motivation, suggesting a trade-off between task ease and engagement. In conclusion the teleoperation system improves the ability for the therapist to interact with the exoskeleton but can disengage the patient.

I. INTRODUCTION

Annually, 15 million individuals globally experience a stroke [1]. Of these cases, 5 million result in fatalities, while another 5 million lead to permanent disabilities. Activities of daily living (ADL) which are fundamental skills required to independently care for oneself, such as eating, bathing, and mobility [2] are often impacted. Neurorehabilitation can facilitate the recovery of lost motor function [3] and help patients regain an independent life by training ADL activities [4]. Recently, advanced rehabilitation strategies have begun to incorporate robotic exoskeletons within a game-like environment, providing a more engaging, interactive framework for patients [5]. Results have shown that robotic therapy can improve upper limb motor functions after strokes [6]–[9]. Robot-aided therapy has been recognized as more effective and

suitable for long-duration rehabilitation without inducing fatigue, compared to manual therapy [10]. Gull et al. [11] provided a full review of upper body exoskeletons and provided a classification of control strategies. These consisted of: assistance (robot supports impaired limb), correction (robot only acts when patients make wrong movements) and resistance (robot restricts the movement of the patient). The ARMin upper-body exoskeleton has a control method where the therapist can move the patient's arm together with the robot on a desired trajectory and then the robot can repeat the trajectory with an adjustable velocity [5]. However, this still does not allow the therapist to directly adjust the movements of the impaired limb during the exercise. Some studies have developed teleoperation systems where the therapist can interact with the robotic device using a haptic device [12]–[15]. Baur et al. [15], developed a novel robot-assisted telerehabilitation system called the "Beam-Me-In Strategy" enabling haptic interaction between therapists and stroke patients over distance. This system utilizes two ARMin exoskeletons where the therapist is attached to one robot and can feel the patient's arm limitations and assess movement impairments remotely. The results showed that the therapists were able to identify abnormal movement patterns from the patients. However, this system does not allow the therapist to directly correct these movements. In addition, this system utilizes two exoskeletons which is expensive and makes the system not modular limiting the therapist to feel the movements of one patient at a time. Zhang et al. [12], developed a tele-rehabilitation system for therapist-in-the-loop training aimed at elbow joint rehabilitation, that integrates a haptic device for therapists, a lightweight exoskeleton for patients, and a visually shared model to deliver patient-specific training strategies and real-time force feedback. The system was tested by two volunteers and the results showed that the therapist could adjust the training strategy and choose to provide assistance or resistance to the patient's elbow.

Despite the efforts to include the therapist in robot therapy, there are still many challenges that remain to make the interaction between patient, robot and therapist as natural and practical as possible. Research has shown that haptic feedback enhances fine motor skills [16]. Combining haptic feedback with virtual reality (VR) has also shown to improve

performance in teleoperation [17].

In this study, we introduce a telerehabilitation system that incorporates a therapist-in-the-loop haptic interface and immersive virtual reality (IVR). This system enables therapists to both monitor and physically interact with the exoskeleton, offering real-time, responsive guidance to patients. Through haptic feedback, therapists can feel and adjust the position of the impaired arm of the patient at two separate locations, the elbow and the wrist. This paper details the development of this system and investigates its impact on the therapist's ability to interact with the patient. We conducted a within-subject human factors study with 36 healthy young participants grouped in pairs. Each participants were assigned the role of "Follower" or "Leader" where the Follower had to reach an arm pose related to an ADL while inside the exoskeleton. The Leader was given a visualization of this ADL pose in IVR and was tasked with guiding the Follower to the correct arm pose under two conditions: demonstration and teleoperation. In the demonstration condition, the Follower could see the Leader displayed on a 2D screen in front of them showing them visually what was the correct pose whereas in the teleoperation condition, there was no visual aid but the Leader could guide the Follower using the haptic device. In both conditions participants could communicate verbally with each other.

We hypothesized that participants would match the correct arm pose faster, more efficiently, and with smoother arm movements in the teleoperation condition compared to the demonstration condition due to the more direct control (1). Additionally, we hypothesized that participants in the Leader role would report a higher workload but more motivation in the teleoperation condition compared to the demonstration condition (2). This is because participant in the Leader role will need to use the haptic device in the teleoperation condition and since they are not familiar with it, this can add a mental load but also create some interest and motivation. For participants in the Follower role, we hypothesized that the teleoperation condition would require less workload and more motivation compared to the demonstration condition (3). This is because in the teleoperation condition they can rely on the haptic feedback to guide them which will require less effort than understanding the visual demonstration from the Leader in the demonstration

condition. Finally, we hypothesized that Followers would find the teleoperation system more usable than the demonstration system, again due to the more direct control but that Leaders would find the demonstration system more usable than the teleoperation system due to the added complexity of the haptic device in the teleoperation condition (4).

II. METHODS

Experimental Procedure

A. Participants

The study received ethical approval from the Human Research Ethics Committee of Delft University of Technology (HREC, Application ID 3928). A total of 36 participants (21 male, 15 female), recruited through word-of-mouth, engaged in the experiment in dyadic configurations. Due to an error in the experimental setup, the first two groups had to be excluded from the analysis, resulting in a final sample of 32 participants distributed across 16 pairs (17 male, 15 female). All participants were students, enrolled either in university or higher professional education programs, and were within the age range of 23 to 33 years. In compliance with ethical guidelines, explicit written consent was obtained from all participants before their involvement in the experiment. Participants were randomly assigned the roles of Leader or Follower by flipping a coin. The Follower was seated and adjusted to the ARMin exoskeleton while the Leader was immersed in VR and tasked with guiding the Follower. Prior experience with IVR was not a requirement.

B. Experimental Task

The goal of the experiment was for the Leader to communicate an arm pose to the Follower as fast and precisely as possible. Within the VR environment, Leaders could view a digital replica of the ARMin, which included a visual representation of the Follower's arm positioned within the exoskeleton. The target arm pose was highlighted in light blue (see Fig. 1), transitioning to green once the Follower's arm reached and maintained the correct pose. The position was considered reached when the wrist and elbow positions of the VR arm inside the digital clone of the ARMin matched the positions of

the target arm within a range of 7 cm. The Follower then needed to maintain the correct position for a duration of 3 seconds for the task to be considered complete. Once completed a new pose appeared until the end of the block (a block comprising of 10 poses).



Fig. 1: Example of experimental task. The target arm is represented in light blue. This is the exultation pose.

The arm poses were modeled after ADL poses [18], specifically: exultation, drinking from a cup, answering the phone, putting a hat on and a hitchhiking gesture (see Fig. 2). Each pose appeared randomly and with a "base position" (a resting posture with the Follower's hand on a virtual table) between each pose. Therefore, in total one block comprised of the 5 ADL poses with 5 base positions in between each of them. Each condition had 3 blocks with two-minute intervals between blocks. For the base position the threshold to match the target arm was relaxed from 7 cm to 10 cm.

C. Experimental Conditions

The experiment was structured around two conditions:

- 1) **Demonstration Condition:** In this setting, the Follower could observe the Leader directly via

a 2D screen (LG, 43" inch, UHD 4K) positioned in front of them. The Leader demonstrated the arm poses with their own arms in front of a webcam (Hama, 2Views). Verbal communication was permitted, restricted to English only.

- 2) **Teleoperation Condition:** In this scenario, the Follower was unable to see the Leader. Instead, the Leader utilized the haptic device to direct the Followers arm into the correct pose. Like the demonstration condition, verbal communication was allowed but limited exclusively to English.

D. Experimental Protocol

The experiment took place in the Motor Learning and Neurorehabilitation (MLN) Lab in the Cognitive Robotics Department of the TU Delft. Upon arrival to the experimental room, participants were welcomed and presented with a small explanation of the experimental setup including a presentation of the exoskeleton and the haptic interface. Participants were then instructed to read and sign the informed consent. After signing the consent forms, the roles of the participants were determined randomly by flipping a coin. Once the roles were determined, the participants were given instructions on how to perform the experiment.

The Follower was told that they would be seated throughout the experiment and that their right arm would be adjusted to the exoskeleton. The Follower was also asked for their body weight so that the correct arm weight compensation could be applied during the experiment. Participants were informed that this was a communication task where the Leader would have to communicate an arm pose to the Follower under two different conditions. Participants were told that there would be five different arm poses with a base pose in between each pose and that we would repeat them three times for each condition with a two-minute break in between each block. Participants were told that this base pose did have to be reached as fast and precisely as the other poses but could be used as a resting position. Participants were told that each condition would have a familiarization phase with three random poses including the base pose in between. Participants were told that they could communicate freely during the experiment in English and that we would record

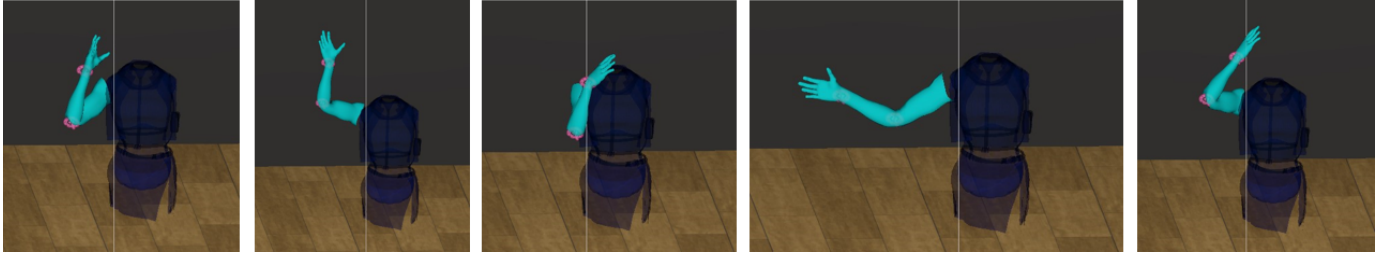


Fig. 2: Representation of all the target poses, from left to right: "phone", "exultation", "drinking from cup", "stop sign" and "putting hat on".

the communication with an audio recorder (Philips, VoiceTracer, 8GB).

After the instructions were given, the Follower was adjusted in the exoskeleton with an explanation of how to activate the exoskeleton and the safety measures required to use the exoskeleton. Once adjusted both participants were required to fill out an initial questionnaire on Qualtrics with some personal information (age, gender, English level, handedness) and any prior experience using the robots or with IVR. Participants were also told that they would need to fill out questionnaires again on Qualtrics after finishing each condition and that at the end of the experiment, we would have a semi-structured interview discussing the experiment.

While participants filled out the initial questionnaire the HMD was calibrated. Depending on the if the Follower was male or female we displayed in the VR environment either a male or female torso (see Appendix C for a visualization). We alternated between pairs which condition we started with. Out of the 18 pairs, eight started with the demonstration condition, and the other eight started with the teleoperation. In the demonstration condition, the Leader was placed in front of the webcam outside of the direct field of view of the Follower. The position was marked on the floor with tape so that the Leader could easily remember where they were positioned. The 2D screen in front of the Follower was switched on and the Leader was asked to move their arms in different directions to check if the Follower could see them on the 2D screen. In the teleoperation condition, the 2D screen was switched off and the Leader was seated in front of the haptic interface again outside of the direct field of view of the Follower. Once seated, we placed the right hand of the Leader on the gripper of the haptic interface and ensured they were correctly seated so that they

could move across the workspace comfortably.

Upon completion of both conditions, participants filled out the questionnaires for the last time and we proceeded with the semi-structured interview. The experiment lasted approximately 90 minutes. For a condensed schematic overview of the timeline of the experiment, refer to Fig. 3 and for a detailed schematic refer to the Appendix (B.1).

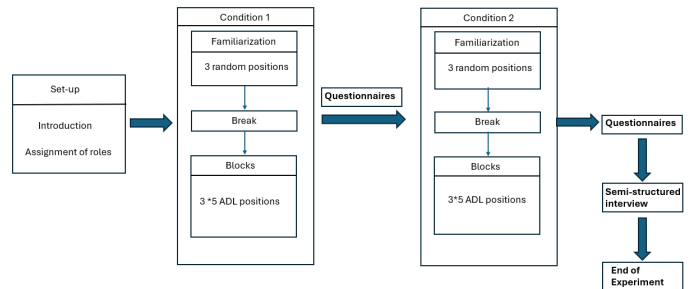


Fig. 3: Schematic overview of the experiment.

Technical Implementation

E. System Overview

The teleoperation system was developed based on a proof-of-concept system designed by N. Kozilius [19]. The therapist is provided with Sigma.7 (Force Dimensions, Switzerland) haptic end-effector device which is bilaterally connected to the ARMin [20] upper-extremity exoskeleton. The Sigma.7 has seven Degrees of Freedom (DoF): 3 translational, 3 rotational, and 1 in the gripper (as found on the spec sheet [21]). The ARMin moves the shoulder and elbow with 4 DoFs and the forearm with 2 DoFs. There are three force/torque sensors attached at the elbow, wrist and hand of the ARMin (F/T Sensor: Mini45, ATI Industrial Automation, Apex, USA). The zero-torque controller was used as the

local controller of the ARMin [22].

The therapist is also provided with a visualization of both robots using a Head Mounted Display (HTC Vive Pro Eye, HTC Vive, Taiwan & Valve, USA) with a field of view of 110 degrees and Dual OLED screens with a resolution of 1440 x 1600 pixels per eye (2880 x 1600 pixels combined). This representation is shown in Fig. 4. The virtual environment was developed with the Unity game engine (Unity Technologies, USA), version 2022.2.15f1. The SteamVR software (version 2.7.3, Valve Corporation, USA) was used to connect the HMD with Unity. Ratschat et al. [23] developed and validated the digital clone of the ARMin. A representation of the patient's arm was added to the environment using First Person Generic Arms Pack from the Unity asset store (the package is now deprecated). A virtual torso for both male (Adventure Character package) and female (Adventure Female) patients was also added. The Final IK package from RootMotion was used to match the movement of the digital clone of the ARMin with the virtual arm. This was done by assigning a wrist target at the end effector of the digital clone of the ARMin and an elbow target located at the elbow joint but slightly below the exoskeleton so the inverse kinematics of the arm are solved in the correct way. The end-effector of the Sigma.7 is represented by a yellow cube. Although the Sigma.7 has 3 rotational degrees of freedom, we excluded them from our system since we used a position-force controller. Therefore the cube did not rotate in the simulation but could only move in the x , y and z directions.

The therapist can "grab" the digital twin at two different locations: the wrist and the elbow. The grabbing points are represented by red spheres on the arm (see Fig. 4). The ARMin can only be grabbed when the therapist is within range (10 cm) of these spheres and actively closes the gripper of the Sigma.7. Once grabbed the spheres turn from red to green indicating that the therapist is now actively interacting with the patient. If at any point the therapist opens the gripper of the Sigma.7, the teleoperation loop exists canceling any interactions.

F. Network

The network setup, shown in Fig. 5, includes three computers linked together using a tp-link 8-port Gigabit network switch (model TL-SG108) and

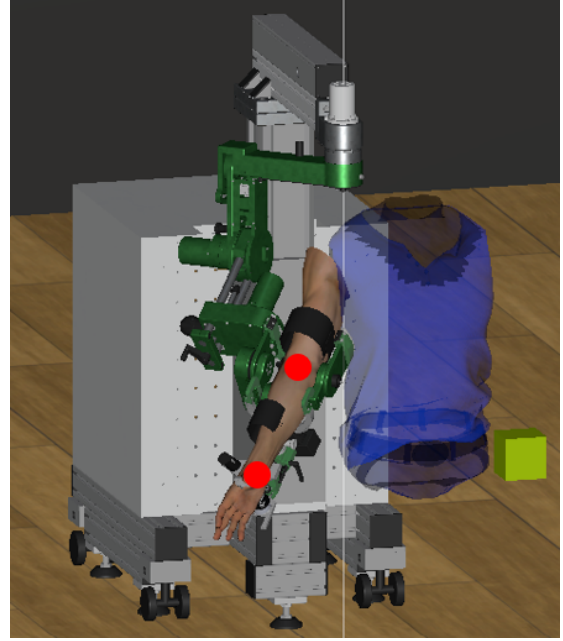


Fig. 4: Visualization of system. The red spheres represent the grabbing points and the yellow cube is the end-effector of the Sigma.7.

Ethernet cables. The ARMin robot is controlled by an 'XPC-Target' computer (Spectra GmbH & Co. KG, RAM: 2 GB, CPU: Intel Core 2, 3 GHz), which runs a Simulink model started from a 'Host' computer (OS: Windows 10, RAM: 32 GB, NVIDIA GeForce RTX 4070 Ti). This Host computer also runs the visualizations in Unity. The tertiary system, referred to as the Linux computer (OS: Ubuntu 22.04, RAM: 32 GB, NVIDIA GeForce RTX 2080 Ti, CPU: AMD Ryzen threadripper 2950x 16-core processor, 3.5GHz), manages the teleoperation control and is connected to the Sigma.7 interface via USB cable. The communication between the computers is done using the User Datagram Protocol (UDP).

From the 'XPC-Target' computer the x , y and z coordinates of the end-effector of the robot as well as the elbow are sent to the Linux computer. These are used in the teleoperation controller to calculate the forces that are applied on the ARMin and on the Sigma.7. The obtained forces on the ARMin are then sent to the 'XPC-Target' with the "GrabbingPoint" which is a variable indicating which point on the exoskeleton has been grabbed. If the end-effector has been grabbed then this variable is 2 and if the elbow has been grabbed, this variable is 1. Since the Sigma.7 is connected via USB cable

to the Linux computer, the x , y and z coordinates of the end-effector are directly extracted and applied in the teleoperation controller. The obtained forces on the Sigma.7 are then sent to the local controller of the Sigma.7. Finally, the positions of the Sigma.7 and of the ARMin are sent to the 'Host' computer for visualization. All the forces were also sent to the 'Host' computer only to be recorded when running the experiment. UDP update rates were recorded on Wireshark (Wireshark 4.2.4). Simulink has an update rate of 3kHz for both the control of ARMin and the UDP communication with the Host. The update rate from Linux to Host and from Linux to Target is around 450 Hz. This was done using a custom UDP class in C++, multithreading was not implemented in this class. This limits the update frequency rate at which the data can be sent to 450 Hz.

G. Teleoperation Controller

The calculations are done with respect to the coordinate frame of the ARMin (Fig. 6). Because the coordinate frame of the Sigma.7 (Fig. 7) is rotated so that the x-axis is parallel to the first revolute axis of the wrist, we need to transform the end-effector position of the Sigma.7 (\vec{X}_s). Therefore, we use a rotation matrix $R_{S,A}$ to rotate the end-effector position of the Sigma.7 around the z-axis by angle θ ($\theta = 45^\circ$).

$$R_{S,A} = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Due to the size difference of the workspace of the two robots, we also scale the workspace of the Sigma.7 by a factor of 10 (C_{scale}). Additionally, we add an offset (\vec{X}_o) upon initialization to overlay the workspace of both robots as closely as possible so that the therapist is always within the workspace of the ARMin to be able to grab the VR arm. The values chosen for this offset are: $\vec{X}_o = [0.34, 0, 1]$ m. This leads to a comprehensive transformation ($\vec{X}_{s,a}^T$) from the local coordinate frame of Sigma.7 to that of ARMin, as detailed in Equation 2.

$$\vec{X}_{s,a}^T = \vec{X}_s \cdot R_{S,A} \cdot C_{scale} + \vec{X}_o \quad (2)$$

As argued by N. Korzilius [19], a bilateral teleoperation control scheme using an impedance control

framework was selected, allowing both the therapist and the patient to experience and exert interaction forces. A PD force-position control approach within the impedance control framework was chosen.

In the impedance control strategy, velocities and forces are computed based on the relative positions and velocities of two systems.

Velocity of each object ($\dot{\vec{X}}$) is computed by the difference in position over time as in equation 3, where \vec{X} and \vec{X}_{prev} are position vectors and Δt is the time step between the current and previous position measurements :

$$\dot{\vec{X}} = \frac{\vec{X} - \vec{X}_{prev}}{\Delta t} \quad (3)$$

The forces applied to the Sigma.7 ($\vec{F}_{s,a}$) and the ARMin (\vec{F}_a) are calculated based on the error in position and velocity between the Sigma.7 and ARMin as in equations 4 and 5 where P_s, B_s and P_a, B_a proportional and damping gain constants for the Sigma.7 and ARMin systems:

$$\vec{F}_{s,a} = -P_s(\vec{X}_{s,a}^T - \vec{X}_a) - B_s(\dot{\vec{X}}_{s,a} - \dot{\vec{X}}_a) \quad (4)$$

$$\vec{F}_a = -P_a(\vec{X}_a - \vec{X}_{s,a}^T) - B_a(\dot{\vec{X}}_a - \dot{\vec{X}}_{s,a}^T) \quad (5)$$

The forces obtained for the Sigma.7 need to be rotated back by the angle θ as in Equation 6:

$$\vec{F}_s = \vec{F}_{s,a} \cdot \begin{bmatrix} \cos -\theta & -\sin -\theta & 0 \\ \sin -\theta & \cos -\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (6)$$

The forces from the ARMin obtained from the teleoperation controller (either at the wrist or elbow) are sent to the 'Target' computer where they are multiplied by the Jacobian so that they are transformed to the joint space of the exoskeleton (refer to Appendix D.0.2 for the Simulink implementation).

The PD gains were determined through empirical testing to enable the therapist to facilitate precise, minor movements, thereby ensuring a safe interaction between the therapist and the patient. The same values for the elbow and wrist control were chosen. Specifically, the proportional gain constants for the Sigma.7 (P_s) and ARMin (P_a) systems were set at 30 N/m and 80 N/m, respectively. Additionally, the damping constants for the Sigma.7 (B_s) and ARMin (B_a) were set at 0.1 Ns/m and 4 Ns/m, respectively.

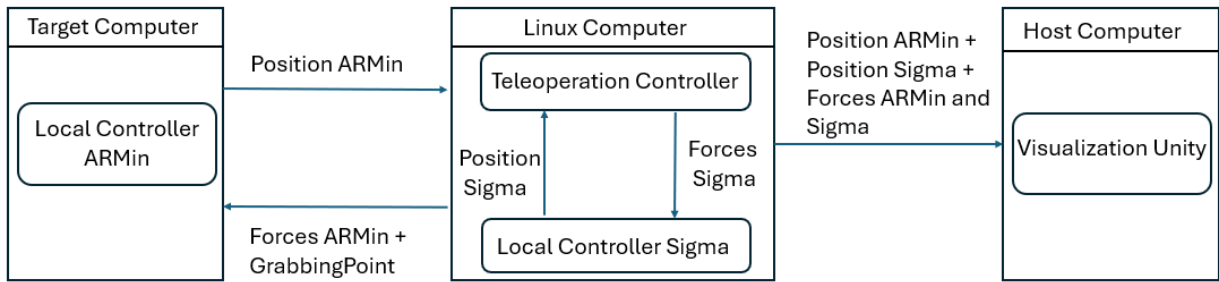


Fig. 5: Schematic of teleoperation network.

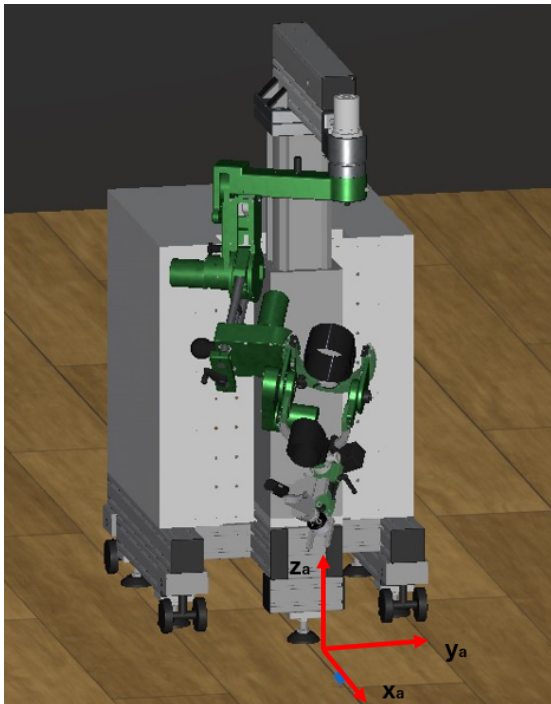


Fig. 6: Cartesian coordinate system of the ARMin controller frame.

H. Arm weight compensation

In total the experiment lasted around 90 minutes, and the Follower was required to spend a lot of time in the exoskeleton moving the arm which is tiring. Therefore, we added 65% arm weight compensation to all the participants. The arm weight compensation was implemented based on previous work by Just et al. [24]. The upper arm and lower arm are treated as two rigid segments that are connected to the robot. The weight of each arm segment is estimated using an anthropometric table (table 7 in [25]) which determines the upper arm and forearm mass as a percent of total body mass. For males the

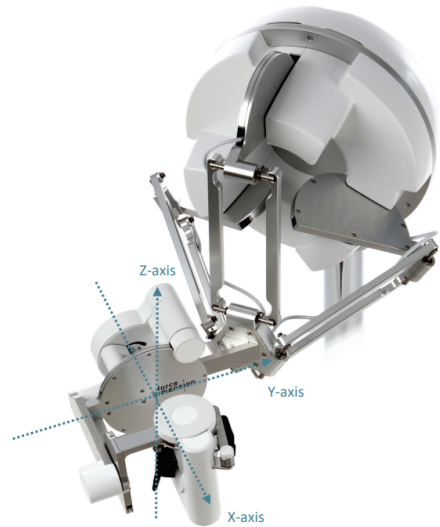


Fig. 7: Cartesian coordinate system of the Sigma.7 haptic device as found in the user manual [21].

upper arm percentage was 2.65% and for females it was 2.6%. The forearm was 1.83% for both males and females. Therefore, to obtain these values we collected the self-reported weight of each participant that was assigned the Follower role and calculated the weight of each segment using a simple Python script. The weight of each segment is multiplied with the respective Jacobian at the cuff location resulting in vertical forces applied at the cuffs in addition to the forces from the local controller of the ARMin.

I. Outcome metrics

All of the data was recorded directly within the Unity environment using the Unity Experimental Framework [26]. The data was recorded at the same frequency rate as the UDP update rate (450

Hz). However, since we were tracking GameObjects within the Unity environment, the update rate of these was limited to 70 Hz. Therefore, the analysis was done with the data recorded at 70 Hz. The GameObjects we were tracking were positioned on the elbow and wrist of the VR arm at the same points that indicated if the position with the target arm was matched or not. The calculations of the completion time, path length was done using Python 3.8.10 (Python Software Foundation, USA). The calculation of the scores of the questionnaires was done in R (R Studio, version 2024.04.1). The statistical analysis (in section *J*) of all the data was also done in R.

1) *Completion time*: To evaluate the effect of haptic feedback on guiding the Follower to the correct arm pose, we recorded the time participants spent achieving the correct arm pose and maintaining it for 3 seconds. The timer started when the target arm appeared and ended after the correct pose was matched for 3 seconds. This was considered a trial.

2) *Path length*: To evaluate how the haptic feedback would impact the efficiency of the task we calculated the total path length the arm of the Follower traveled during a trial at both the elbow and wrist location. This is achieved by calculating the sum of Euclidean distances between consecutive points.

3) *Movement smoothness*: The analysis of movement smoothness was conducted in a manner consistent with the methodology described in [23], owing to the similarity in data collected. Movement smoothness was assessed using the Spectral ARC length (SPARC) [27], where lower SPARC values denote higher smoothness. To obtain SPARC values, we needed to obtain the velocity profile. This involved calculating several parameters from the data points. Displacement is determined as the Euclidean distance between consecutive positions by considering the differences in x, y, and z coordinates. The time interval is the difference in time between these consecutive data points. Velocity is then calculated by dividing the displacement by the time interval, providing a raw measure of speed for each data point. The velocity time series underwent a first-order low-pass Butterworth filtering process with a 20 Hz cutoff frequency, appropriate since 98% of human activities fall below 10 Hz [28]. For SPARC calculation, the cutoff frequency was set at

a maximum of $w_{max} = 20\text{Hz}$, and the amplitude threshold was established at $V = 0.05$.

4) *Questionnaires*: Both participants were given the same questionnaire at the end of each condition. Motivation is a crucial factor influencing effort and engagement in robotic training for stroke patients [29]. Therefore, we incorporated elements from the Interest/Enjoyment and Perceived Competence subscales of the Intrinsic Motivation Inventory (IMI) [30] into our questionnaire. Each question is measured with a 7-point subscale ranging from 1 - not at all true to 7 - very true.

We also utilized the raw NASA Task Load Index (RTLX) [31] to evaluate the mental load of the system on both participants. The RTLX evaluates six distinct domains: mental, physical, and temporal demand (the latter referring to perceived time pressure), as well as perceived performance, effort (the effort required to achieve the performance), and frustration level. Each domain is measured using a single 21-point Likert-style scale. On this scale, a score of zero indicates "very low", and a score of 20 indicates "very high" [32].

Finally, we assessed the participants' subjective perception of the system's usability with the System Usability Scale (SUS) questionnaire [33] which consists of ten five-point Likert-style items. All questionnaire scores were adjusted to a scale from 0 to 100 to simplify the interpretation of the results. The questionnaire data was collected using the Qualtrics software (2024 Qualtrics).

5) *Recordings*: We recorded the communication between the participants while they were performing the task under the two conditions. In addition we conducted a semi-structured interview at the of the experiment to gather some feedback. The recordings were not analysed. Some insights from the semi-structured interviews is given in the discussion.

J. Statistical Analysis

In total, we recorded 480 trials (16 participants x five poses x three trials x two conditions). For each outcome metric, we excluded outliers from each condition separately with values $< Q1 - 1.5IQR$ or values $> Q3 + 1.5IQR$, where IQR is the interquartile range, and $Q1$ and $Q3$ are the first and third quartiles, respectively.

We employed linear mixed models (LMEs) using the *lmerTest* package [34] in R to evaluate whether

participants performed differently when attempting to match the target pose depending on the condition (demonstration or teleoperation), the poses that they were attempting to match (using the drinking cup pose as a reference), and the trial repetition (1-3). We included the poses as a fixed effect to investigate whether the participants' performance differed between the poses since some poses may have been harder to match regardless of the condition. The trial repetition was added as a fixed effect to investigate whether learning effects existed between the three repetitions for each pose. We also added the condition order as a fixed effect to determine if starting with a certain condition lead to an advantage. Furthermore, we investigated the interaction effect between poses, condition and the condition order to establish whether some poses were easier to match depending on the condition and condition order. To account for inter-participant variability, we incorporated participants as a random effect. The model is described by the following equation:

$$\text{Outcome_measure} \sim \text{Condition} \times \text{Pose} \quad (7) \\ + \text{Condition_Order} + \text{Trial} + (1|\text{Participant})$$

To establish whether there were differences between the two conditions in the participants' perceived workload, motivation and the system's usability the participants' RTLX, IMI and SUS scores were also tested using LMEs. The role of the participant and the condition was added as fixed effects. We also investigated the interaction effect between role and condition. To account for inter-participant variability, we incorporated participants as a random effect. The model is described by the following equation:

$$\text{Questionnaire_Score} \sim \text{Role} \times \text{Condition} \\ + (1|\text{Participant}) \quad (8)$$

Post hoc multiple comparison analyses were performed on the questionnaire results when significant effects were found using the *emmeans* package with FDR correction [35] for multiple comparisons. The significance level was set to $\alpha = 0.05$.

III. RESULTS

Out of 480 measurements per outcome measure, the outlier removal led to the following reductions:

For Total Time, 11 measurements were removed for the demonstration condition and 18 for the teleoperation condition. For Path Length, at the elbow location, 10 measurements were removed for the demonstration condition and 22 for the teleoperation condition, while at the hand location, 21 measurements were removed for the demonstration condition and 22 for the teleoperation condition. For SPARC, at the elbow location, 9 measurements were removed for the demonstration condition and 7 for the teleoperation condition, and at the hand location, 6 measurements were removed for the demonstration condition and 5 for the teleoperation condition. Due to the extensive statistical analysis, we only reported statistically significant or interesting results. For a complete picture of all effects and their estimates, please refer to the tables in the Appendix (section A).

A. Time to reach pose

The analysis revealed several significant findings. The average total time to complete a trial was 20.01 seconds. It took on average participants 11.3 seconds faster to complete the task in the teleoperation condition compared to the demonstration condition which was statistically significant ($p = 0.0247$). Additionally, participants became faster with each trial (see Fig. 8), but the results were only significant when comparing the first and third trials (estimate = -2.12 seconds, $p = 0.0141$). In contrast, the type of pose (exultation, phone, putting hat on, stop sign) did not significantly affect completion time (all p-values > 0.2). Similarly, the order in which participants experienced the conditions and all interaction effects were not significant (all p-values > 0.05).

B. Path Length

1) *Elbow Location*: At the elbow location, participants traveled on average 0.65 meters to complete a trial. The teleoperation condition did not increase the path length significantly ($p = 0.711$). Additionally, participants reduced the path length with each trial (see Fig. 9), but the results were only significant when comparing the first and third trials (estimate = -0.06 meters, $p = 0.0394$). The type of pose (exultation, phone, putting hat on, stop sign) did not significantly affect the path length (all p-values > 0.05 except for putting hat on which

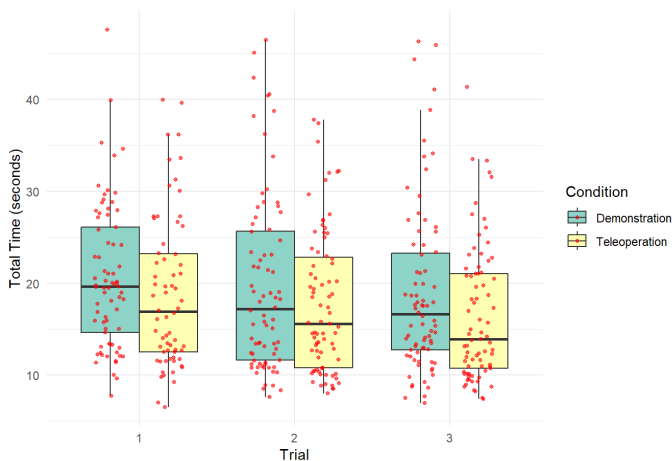


Fig. 8: Total Time by Trial.

approached significance, $p = 0.0686$). Similarly, the order in which participants experienced the conditions and all interaction effects were not significant (all p -values > 0.05).

2) *Hand Location*: At the hand location, participants had a longer path length compared to the elbow location with an average of 1.11 meters per trial. The teleoperation condition did not significantly decrease the path length ($p = 0.804$) Consistent with the previous findings, participants again significantly reduced their path length on the third trial (see Fig. 9) compared to the first trial (estimate = -0.11 meters, $p = 0.0176$).

The type of pose (exultation, phone, putting hat on, stop sign) did not significantly affect the path length (all p -values > 0.05). Similarly, the order in which participants experienced the conditions and all interaction effects were not significant (all p -values > 0.05).

C. SPARC

1) *Elbow Location*: The average SPARC value at the elbow location for a trial was found to be -4.42 . The SPARC did not significantly increase in the teleoperation condition ($p = 0.579$). The Pose effect for phone was significant with an estimate of -3.56 ($p = 0.0217$). Additionally, the trial effects were significant for both the second trial (estimate = 0.82 , $p = 0.00228$) and the third trial (estimate = 0.84 , $p = 0.00176$). Furthermore, the Pose Order interaction was significant for the phone pose (estimate = 2.18 , $p = 0.0261$).

All other main and interaction effects were not significant.

2) *Hand Location*: At the hand we found a lower SPARC value compared to the elbow location with an average value of -6.13 for a trial. The teleoperation condition increased on average the SPARC value by 2.70 for a trial (see Fig. 10) and almost reached significance ($p = 0.0778$). The Trial effects were significant for both the second trial (estimate = 0.54 , $p = 0.0401$) and the third trial (estimate = 0.70 , $p = 0.00792$).

All other main and interaction effects were not significant.

D. Questionnaire

In the following results we first look at if there are statistically significant results between the roles, conditions and the interaction effect. If the results are statistically significant, we look at the results from the post-hoc analysis. For a complete picture of all effects and their estimates, please refer to the tables in the Appendix (section A).

1) *Workload (RTLX)*: We found that being a Leader significantly increases the mental demand score by 30 points compared to being a Follower ($p = 0.000186$). We found that the teleoperation condition alone does not significantly alter the mental demand compared to the demonstration condition ($p = 0.871$). The interaction effect is not significant, indicating that the difference in mental demand between Leaders and Followers is consistent across both conditions ($p = 0.674$). The post-hoc analysis revealed that the decrease in mental demand when moving from demonstration to teleoperation for Leaders is not significant ($p = 0.870$).

We found that being a Leader did not significantly decrease the physical effort ($p = 0.364$). We did find that the teleoperation condition significantly reduced the physical effort ($p = 0.0171$). The interaction effect was not significant ($p = 0.207$). The post-hoc analysis did not reveal any significant differences. We did find a decrease in the physical effort from the Follower when changing from the demonstration to the teleoperation condition ($p = 0.0762$).

We found that being a Leader did not significantly increase the effort ($p = 0.363$). We did find that the teleoperation condition significantly decreased the effort by 28 points ($p = 0.000736$). The interaction effect did not show any significant results

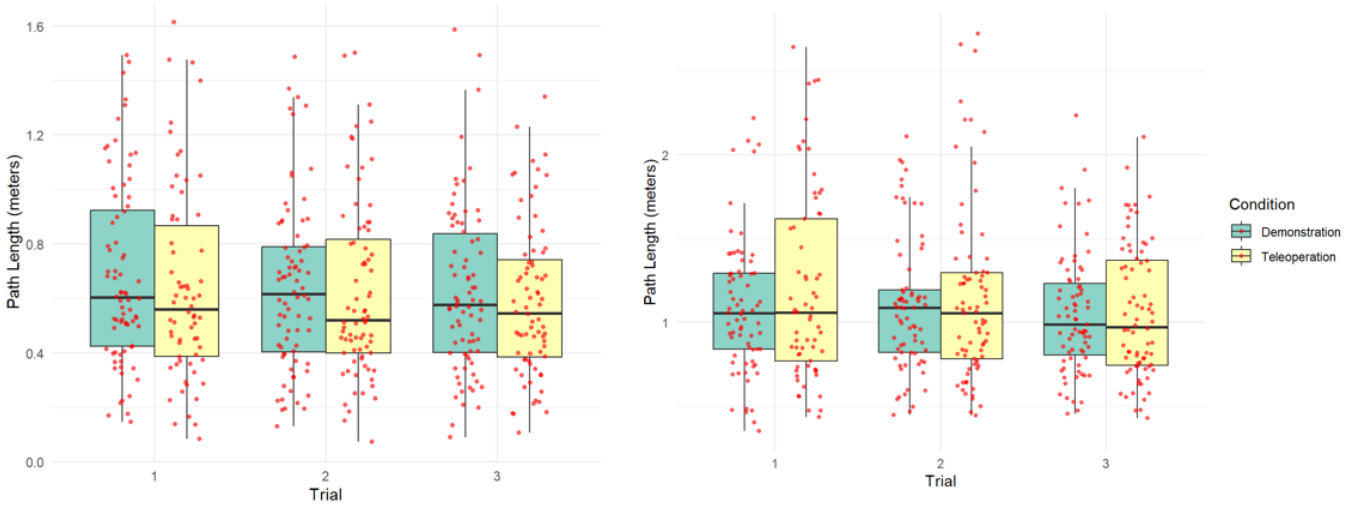


Fig. 9: Path Length by trial for elbow location on the left and hand location on the right.

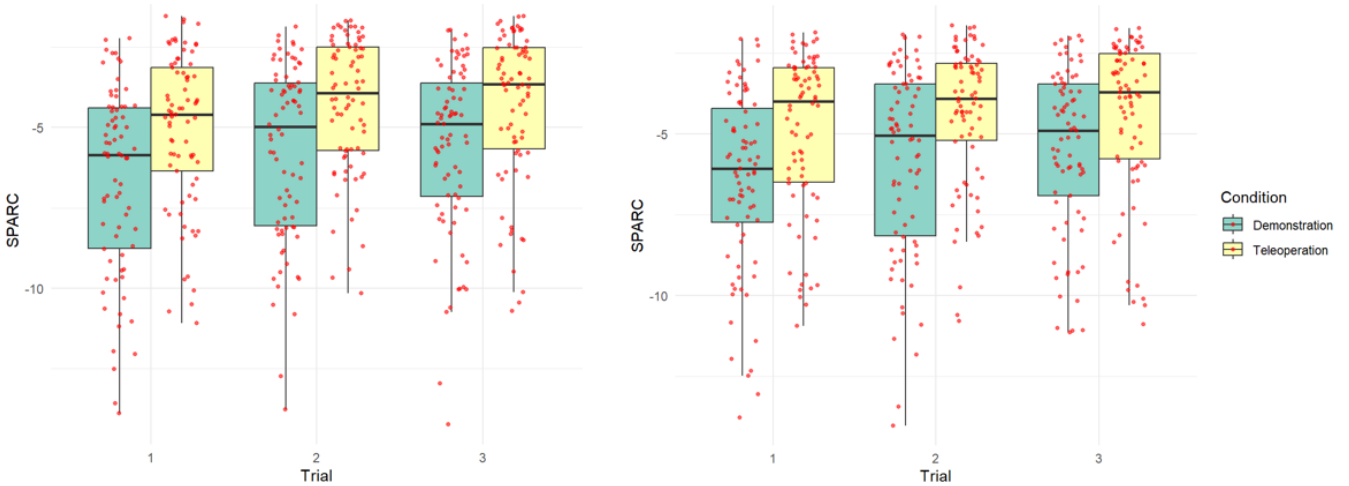


Fig. 10: SPARC by trial for elbow location on the left and hand location on the right.

($p = 0.0898$). The post-hoc analysis revealed that the Follower experienced a significant increase in effort in the demonstration condition compared to the teleoperation condition ($p = 0.00390$).

We did not find any significant results in the temporal demand, performance or frustration subcategories. Fig. 11 depicts the results of the workload for both Follower and Leader roles and separating both conditions.

2) *Usability (SUS)*: The results for the SUS scores did not show any statistically significant outputs. Leaders found the demonstration and teleoperation systems in general a bit more usable than Followers according to the mean scores (refer to the Appendix A.4.1).

3) *Motivation (IMI)*: The intrinsic motivation results showed that the Leader role did not significantly increase effort ($p = 0.450$), however the teleoperation condition significantly increased the effort ($p < 0.0001$). We also found significant differences in the interaction effects ($p = 0.0149$). The post-hoc analysis revealed that the Follower put significantly more effort in the demonstration condition compared to the teleoperation condition ($p = 0.0001$).

In the perceived competence sub-category, we did not find significant differences in the Leader role ($p = 0.448$) or between the conditions ($p = 0.774$). However, we did find significance in the interaction effects ($p = 0.00209$). Post-hoc analysis revealed that the Leader rated a significantly higher perceived

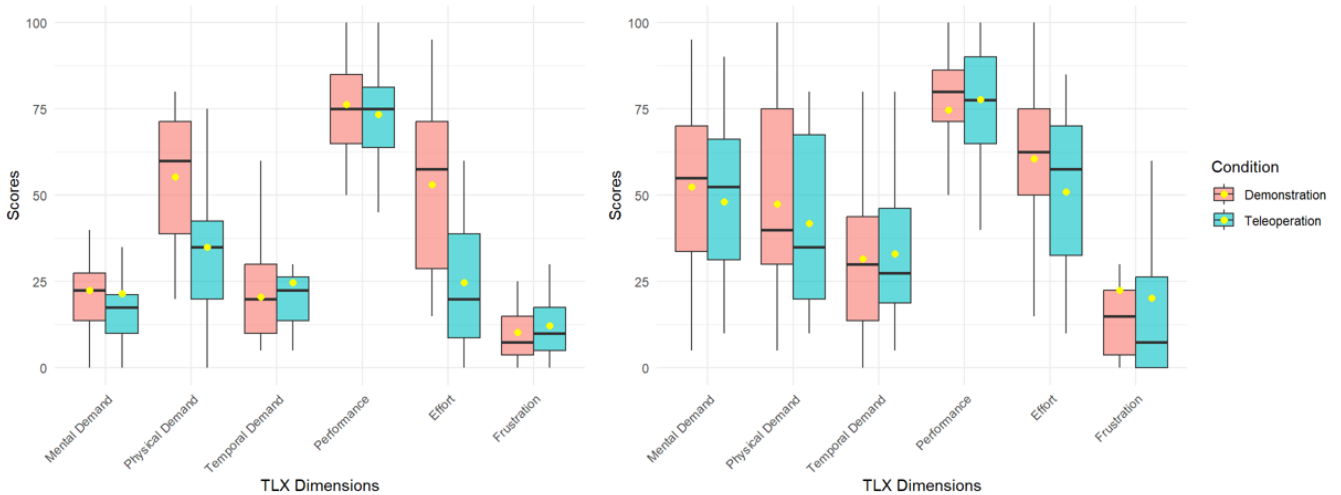


Fig. 11: RAW-NASA-TLX Results: Follower on the left and Leader on the right.

competence in the teleoperation condition compared to the demonstration condition ($p = 0.0003$). The results can be seen in Fig. 12.

IV. DISCUSSION

A. The Teleoperation Condition Significantly Decreased the Total Time Required to Complete a Trial and Improved Efficiency and Movement Smoothness

The results partially validate our first hypothesis (1) that the participants would match the correct arm pose faster, more efficiently and with smoother arm movements in the teleoperation condition compared to the demonstration condition. Although we saw a decrease in total time, shorter path length and smoother arm movements, the results are only statistically significant for the total time. Replacing the visual feedback with the haptic feedback seemed to improve the ability of the Leader to guide the Follower to the correct arm pose much faster. These results align with findings from Feygin et al. [36] that showed that haptic training was more effective than visual training with respect to timing. Several participants reported in the semi-structured interviews that the baseline controller of the ARMin was not always stable and that it took time to adapt. The controller of the teleoperation system was stable so when the Leader grasped the Follower, this helped stabilize the movements which can explain in part the smoother arm movements in the teleoperation condition. We also saw an overall improvement across trials, suggesting a learning effect and an adaptation to the system. From the path length

results it seems that when grasping; the Leader did not always take the shortest path. Leaders were not able to move the VR camera around the environment to have a clear perspective of the depth of the environment and several participants did report in the semi-structured interview that they at times struggled to located the exact position of the arm. In the demonstration condition, Leaders had to mirror the arm pose seen in the VR to their own arm to demonstrate the pose which could explain why this would have added some more time to perform the task. Leaders did report a higher workload across all the subcategories of the RTLX in the demonstration condition compared to the teleoperation condition which indicates that this condition was more demanding and time consuming.

B. Leaders experienced less workload and more motivation under the teleoperation condition

In our second hypothesis (2) we suspected that the novelty with the haptic combined with the IVR and having to guide the Follower to a specific arm pose would increase the workload for the Leaders. Surprisingly, the results from the NASA-TLX suggest that the Leader experience less overall workload in the teleoperation condition in comparison to the demonstration condition. Although the results are not significant, these still suggest that the added haptic feedback was beneficial enough for the task itself that the novelty in the system did not disturb the participants.

The results from the IMI questionnaire suggest that

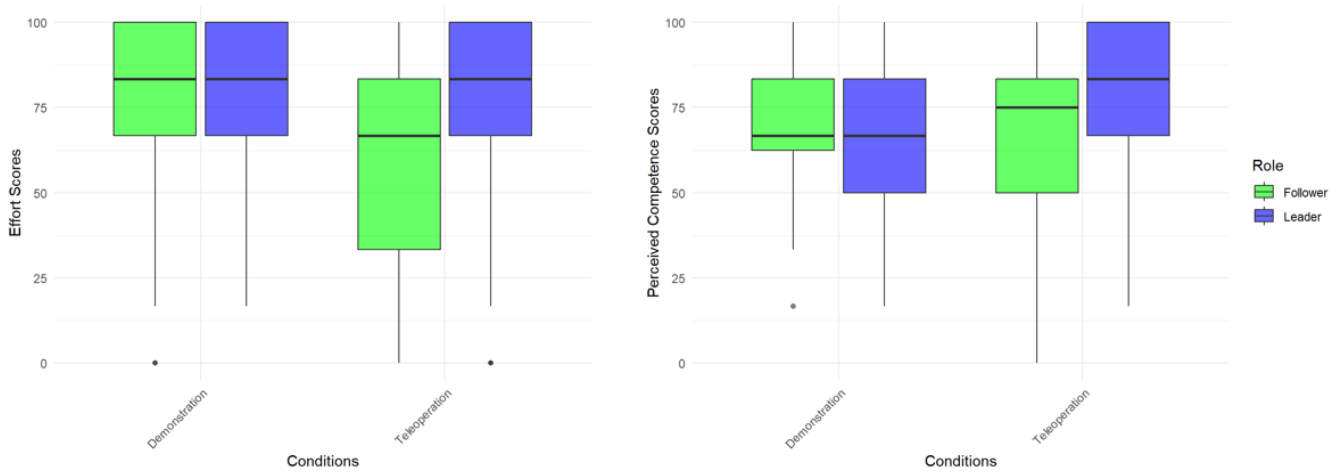


Fig. 12: IMI Results, effort on the left and perceived competence on the right.

the Leaders had more motivation in the teleoperation condition compared to the demonstration condition as hypothesised (2). Although the results were not significant in the "effort" subcategory we did find significant results in the "perceived competence" subcategory. These results suggest that the haptic feedback provides a more motivating environment for the therapist to interact with the patient.

C. Followers Experienced Less Workload and Also Less Motivation in the Teleoperation Condition

The results from the RTLX suggest that the Follower experienced less workload in the teleoperation compared in most subcategories as we hypothesised (3). Followers did rate the teleoperation condition as having a higher temporal demand and being more frustrating in comparison to the demonstration condition. The IMI results suggest that the Follower put less effort in the teleoperation condition which contradicts our third hypothesis. The teleoperation condition required much less effort from the Followers perspective since they could be guided by the Leader. This made participants lose some interest in the task since they could be mostly passive during this condition. In the semi-structured interview some participants reported "closing their eyes" during this condition and "letting themselves be guided" aligning with the results from the questionnaires.

D. Leaders and Followers did not Perceived Significant Differences in the Usability of Both Systems

The SUS scores did not show significant differences between the demonstration and teleoperation conditions for either role (4). The mean score for Leaders in the demonstration and teleoperation conditions was found to be 71.41 and 71.25 respectively which are both high scores. Similarly the mean scores for the Followers was found to be 65.62 and 67.19 for the demonstration and teleoperation conditions respectively. The fact that there was no significant differences even though the teleoperation condition had an added haptic device which participants were not all familiar with indicates that the system was easy to use with very little training. The fact that we found a significant shorter time to complete the task in the teleoperation condition is also an indication that the system was intuitive.

E. Limitations and Future Work

The arm weight estimation was done using an anthropometric table based on the total body weight of the participant. A more accurate measure of the participant's arm weight could have provided better arm weight support during the experiment. We did not include the possibility for participants to move the camera around the VR environment. This could have provided Leaders with a better depth estimation of the target arm pose. Some participants reported in the semi-structured interview that they had difficulties aligning the Follower arm with the target arm due to not perceiving the depth of the

environment correctly. A full thematic analysis of the audio recordings still needs to be done. There can be many interesting insights from the communication between the two participants. Additionally, we recorded which point on the arm (elbow or wrist) the Leader grabbed during the experiment. It could be interesting to see if one point was grabbed more than the other in general or for specific poses. A post-hoc analysis on the outcome measures (total time, path length and SPARC) still needs to be done and could reveal interesting findings. Our participants were all university students, with a technical background. A more diverse population sample would be better to account for participant variability.

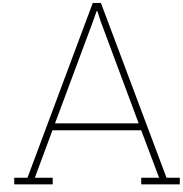
V. CONCLUSIONS

The study introduces a novel approach for therapists to interact with stroke patients when using an upper-body exoskeleton. We conducted an experiment with healthy individuals, in pairs to assess how this teleoperation system with haptic feedback could enhance the capabilities of the therapist to interact with the patient. Our results indicate that the haptic teleoperation system combined with IVR seems to allow for the therapist to have better control over the patient's movement. Although the patient seems to lose some motivation due to the therapist taking over some of the movement the results are encouraging. In future work, the patient could also be immersed in IVR as this has been shown to increase motivation [37].

REFERENCES

- [1] [Online]. Available: <https://www.emro.who.int/health-topics/stroke-cerebrovascular-accident/index.html>
- [2] P. F. Edemekong, D. Bomgaars, S. Sukumaran, and S. B. Levy, "Activities of daily living," 2019.
- [3] P. Langhorne, J. Bernhardt, and G. Kwakkel, "Stroke rehabilitation," *The Lancet*, vol. 377, no. 9778, pp. 1693–1702, 2011.
- [4] A. Rojo, J. Á. Santos-Paz, Á. Sánchez-Picot, R. Raya, and R. García-Carmona, "Farmday: A gamified virtual reality neurorehabilitation application for upper limb based on activities of daily living," *Applied Sciences*, vol. 12, no. 14, p. 7068, 2022.
- [5] T. Nef, M. Mihelj, and R. Riener, "Armin: a robot for patient-cooperative arm therapy," *Medical & biological engineering & computing*, vol. 45, pp. 887–900, 2007.
- [6] G. Kwakkel, B. J. Kollen, and H. I. Krebs, "Effects of robot-assisted therapy on upper limb recovery after stroke: a systematic review," *Neurorehabilitation and neural repair*, vol. 22, no. 2, pp. 111–121, 2008.
- [7] M. A. Finley, S. E. Fasoli, L. Dipietro, J. Ohlhoff, L. MacClellan, C. Meister, J. Whitall, R. Macko, C. T. Bever Jr, H. I. Krebs, et al., "Short-duration robotic therapy in stroke patients with severe upper-limb motor impairment," *Journal of Rehabilitation Research & Development*, vol. 42, no. 5, 2005.
- [8] P. Staubli, T. Nef, V. Klamroth-Marganska, and R. Riener, "Effects of intensive arm training with the rehabilitation robot armin ii in chronic stroke patients: four single-cases," *Journal of neuroengineering and rehabilitation*, vol. 6, pp. 1–10, 2009.
- [9] F. Molteni, G. Gasperini, G. Cannaviello, and E. Guanziroli, "Exoskeleton and end-effector robots for upper and lower limbs rehabilitation: narrative review," *PM&R*, vol. 10, no. 9, pp. S174–S188, 2018.
- [10] R. W. Teasell and L. Kalra, "What's new in stroke rehabilitation," *Stroke*, vol. 35, no. 2, pp. 383–385, 2004.
- [11] M. A. Gull, S. Bai, and T. Bak, "A review on design of upper limb exoskeletons," *Robotics*, vol. 9, no. 1, p. 16, 2020.
- [12] S. Zhang, Q. Fu, S. Guo, and Y. Fu, "A telepresence system for therapist-in-the-loop training for elbow joint rehabilitation," *Applied Sciences*, vol. 9, no. 8, p. 1710, 2019.
- [13] Z. Yang and S. Guo, "Premilitary performance evaluation of model-mediated telerehabilitation system with task stiffness estimation," in *2023 IEEE International Conference on Mechatronics and Automation (ICMA)*. IEEE, 2023, pp. 467–472.
- [14] Y. Liu, S. Guo, Z. Yang, H. Hirata, and T. Tamiya, "A home-based tele-rehabilitation system with enhanced therapist-patient remote interaction: A feasibility study," *IEEE Journal of Biomedical and Health Informatics*, vol. 26, no. 8, pp. 4176–4186, 2022.
- [15] K. Baur, N. Rohrbach, J. Hermsdörfer, R. Riener, and V. Klamroth-Marganska, "The âbeam-me-in strategyâ–remote haptic therapist-patient interaction with two exoskeletons for stroke therapy," *Journal of neuroengineering and rehabilitation*, vol. 16, pp. 1–15, 2019.
- [16] F. Danion, J. S. Diamond, and J. R. Flanagan, "The role of haptic feedback when manipulating nonrigid objects," *Journal of neurophysiology*, vol. 107, no. 1, pp. 433–441, 2012.
- [17] V. Nitsch and B. Färber, "A meta-analysis of the effects of haptic interfaces on task performance with teleoperation systems," *IEEE transactions on haptics*, vol. 6, no. 4, pp. 387–398, 2012.
- [18] A. Schwarz, M. M. Bhagubai, S. H. Nies, J. P. Held, P. H. Veltink, J. H. Buurke, and A. R. Luft, "Characterization of stroke-related upper limb motor impairments across various upper limb activities by use of kinematic core set measures," *Journal of neuroengineering and rehabilitation*, vol. 19, pp. 1–18, 2022.
- [19] N. Korzilius, "Telerehabilitation design and evaluation on stability and transparency," MSc Thesis, Delft University of Technology, Delft, Netherlands, 2023. [Online]. Available: <http://resolver.tudelft.nl/uuid:55d5ed46-64c5-4965-9311-49b6050ef2ca>
- [20] F. Just, Ö. Özen, P. Bösch, H. Bobrovsky, V. Klamroth-Marganska, R. Riener, and G. Rauter, "Exoskeleton transparency: feed-forward compensation vs. disturbance observer," *at-Automatisierungstechnik*, vol. 66, no. 12, pp. 1014–1026, 2018.
- [21] *Force Dimension sigma.7 User Manual*. [Online]. Available: <https://www.forcedimension.com/products/sigma>
- [22] S. Dalla Gasperina, A. L. Ratschat, and L. Marchal-Crespo, "Quantitative and qualitative evaluation of exoskeleton transparency controllers for upper-limb neurorehabilitation," in *2023 International Conference on Rehabilitation Robotics (ICORR)*. IEEE, 2023, pp. 1–6.
- [23] A. Ratschat, T. M. Lomba, S. Dalla Gasperina, and L. Marchal-Crespo, "Development and validation of a kinematically ac-

- curate upper-limb exoskeleton digital twin for stroke rehabilitation,” in *2023 International Conference on Rehabilitation Robotics (ICORR)*. IEEE, 2023, pp. 1–6.
- [24] F. Just, Ö. Özen, S. Tortora, V. Klamroth-Marganska, R. Riener, and G. Rauter, “Human arm weight compensation in rehabilitation robotics: efficacy of three distinct methods,” *Journal of neuroengineering and rehabilitation*, vol. 17, pp. 1–17, 2020.
- [25] R. Drillis, R. Contini, and M. Bluestein, “Body segment parameters,” *Artificial limbs*, vol. 8, no. 1, pp. 44–66, 1964.
- [26] J. Brookes, M. Warburton, M. Alghadier, M. Mon-Williams, and F. Mushtaq, “Studying human behavior with virtual reality: The unity experiment framework,” *Behav. Res. Methods*, vol. 52, pp. 455–463, 2019.
- [27] S. Balasubramanian, A. Melendez-Calderon, A. Roby-Brami, and E. Burdet, “On the analysis of movement smoothness,” *Journal of neuroengineering and rehabilitation*, vol. 12, pp. 1–11, 2015.
- [28] E. K. Antonsson and R. W. Mann, “The frequency content of gait,” *Journal of biomechanics*, vol. 18, no. 1, pp. 39–47, 1985.
- [29] M. Sivan, J. Gallagher, S. Makower, D. Keeling, B. Bhakta, R. J. O’Connor, and M. Levesley, “Home-based computer assisted arm rehabilitation (hcaar) robotic device for upper limb exercise after stroke: results of a feasibility study in home setting,” *Journal of neuroengineering and rehabilitation*, vol. 11, pp. 1–17, 2014.
- [30] E. McAuley, T. Duncan, and V. V. Tammen, “Psychometric properties of the intrinsic motivation inventory in a competitive sport setting: A confirmatory factor analysis,” *Research quarterly for exercise and sport*, vol. 60, no. 1, pp. 48–58, 1989.
- [31] S. G. Hart, “Nasa-task load index (nasa-tlx); 20 years later,” in *Proceedings of the human factors and ergonomics society annual meeting*, vol. 50, no. 9. Sage publications Sage CA: Los Angeles, CA, 2006, pp. 904–908.
- [32] R. Rätz, A. L. Ratschat, N. Cividanes-Garcia, G. M. Ribbers, and L. Marchal-Crespo, “Designing for usability: development and evaluation of a portable minimally-actuated haptic hand and forearm trainer for unsupervised stroke rehabilitation,” *Frontiers in neurorobotics*, vol. 18, p. 1351700, 2024.
- [33] J. Brooke *et al.*, “Sus-a quick and dirty usability scale,” *Usability evaluation in industry*, vol. 189, no. 194, pp. 4–7, 1996.
- [34] A. Kuznetsova, P. B. Brockhoff, and R. H. B. Christensen, “lmerTest package: tests in linear mixed effects models,” *Journal of statistical software*, vol. 82, no. 13, 2017.
- [35] Y. Benjamini and D. Yekutieli, “The control of the false discovery rate in multiple testing under dependency,” *Annals of statistics*, pp. 1165–1188, 2001.
- [36] D. Feygin, M. Keehner, and R. Tendick, “Haptic guidance: Experimental evaluation of a haptic training method for a perceptual motor skill,” in *Proceedings 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. HAPTICS 2002*. IEEE, 2002, pp. 40–47.
- [37] K. A. Buetler, J. Penalver-Andres, Ö. Özen, L. Ferriroli, R. M. Müri, D. Cazzoli, and L. Marchal-Crespo, “@tricking the brain@ using immersive virtual reality: Modifying the self-perception over embodied avatar influences motor cortical excitability and action initiation,” *Frontiers in human neuroscience*, vol. 15, p. 814, 2022.



Statistical Analysis

A.1. Total Time

Table A.1: Fixed Effects Results Total Time

	Estimate	Std. Error	df	t value	Pr(> t)	
(Intercept)	20.0147	4.7324	56.1519	4.229	8.73e-05	***
ConditionSigma	-11.3090	5.0162	413.3771	-2.254	0.0247	*
Poseexultation	-5.1453	4.9453	413.3159	-1.040	0.2987	
Posephone	2.7989	4.8483	413.1497	0.577	0.5641	
Poseputting hat on	6.0518	4.9005	413.2446	1.235	0.2176	
PoseStop sign	2.0352	4.8946	413.1590	0.416	0.6778	
Condition_Order	1.7800	2.9706	54.6020	0.599	0.5515	
Trial2	-1.1799	0.8612	413.5549	-1.370	0.1714	
Trial3	-2.1207	0.8604	413.4490	-2.465	0.0141	*
ConditionSigma:Poseexultation	5.3663	7.0158	413.4101	0.765	0.4448	
ConditionSigma:Posephone	2.0586	6.9276	413.1848	0.297	0.7665	
ConditionSigma:Poseputting hat on	-0.0493	6.9517	413.2347	-0.007	0.9943	
ConditionSigma:PoseStop sign	4.7600	7.0065	413.2285	0.679	0.4973	
ConditionSigma:Condition_Order	5.6930	3.1719	413.3510	1.795	0.0734	.
Poseexultation:Condition_Order	2.5949	3.1171	413.2989	0.832	0.4056	
Posephone:Condition_Order	-4.0971	3.0662	413.1585	-1.336	0.1822	
Poseputting hat on:Condition_Order	-5.3498	3.0994	413.2581	-1.726	0.0851	.
PoseStop sign:Condition_Order	-2.6138	3.1390	413.1766	-0.833	0.4055	
ConditionSigma:Poseexultation:Condition_Order	-3.7185	4.4695	413.3954	-0.832	0.4059	
ConditionSigma:Posephone:Condition_Order	-0.5488	4.3746	413.1840	-0.125	0.9002	
ConditionSigma:Poseputting hat on:Condition_Order	1.1960	4.4101	413.2230	0.271	0.7864	
ConditionSigma:PoseStop sign:Condition_Order	-2.3308	4.4618	413.2425	-0.522	0.6017	

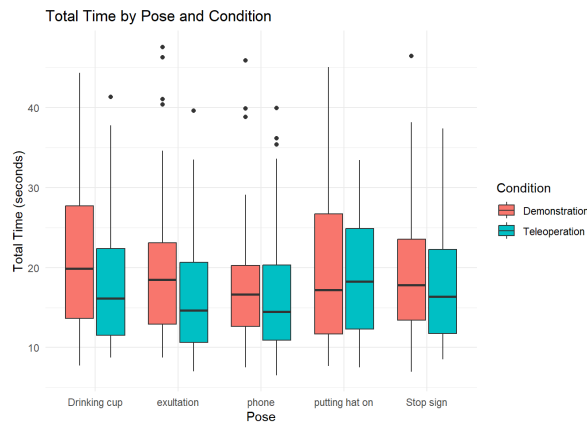


Figure A.1: Total Time per ADL Poses

A.2. Path Length

Table A.2: Fixed Effects Results Elbow Location

	Estimate	Std. Error	df	t value	Pr(> t)	
(Intercept)	0.65466	0.17707	41.30292	3.697	0.000635	***
ConditionSigma	0.06299	0.17015	411.93652	0.370	0.711434	
Poseexultation	-0.11396	0.17225	411.97413	-0.662	0.508614	
Posephone	-0.01013	0.16991	411.89760	-0.060	0.952476	
Poseputting hat on	0.31023	0.16991	411.89760	1.826	0.068597	.
PoseStop sign	-0.28905	0.16877	411.83389	-1.713	0.087514	.
Condition_Order	0.03301	0.11173	40.93930	0.295	0.769171	
Trial2	-0.03927	0.03016	412.14141	-1.302	0.193602	
Trial3	-0.06218	0.03009	412.28606	-2.067	0.039404	*
ConditionSigma:Poseexultation	-0.25418	0.24251	411.97440	-1.048	0.295197	
ConditionSigma:Posephone	-0.19441	0.24072	411.88907	-0.808	0.419789	
ConditionSigma:Poseputting hat on	-0.25742	0.24083	411.92215	-1.069	0.285741	
ConditionSigma:PoseStop sign	0.10471	0.23856	411.83709	0.439	0.660954	
ConditionSigma:Condition_Order	-0.04315	0.10959	412.07854	-0.394	0.693986	
Poseexultation:Condition_Order	0.12007	0.10933	412.02528	1.098	0.272737	
Posephone:Condition_Order	-0.04145	0.10748	411.90552	-0.386	0.699948	
Poseputting hat on:Condition_Order	-0.10281	0.10748	411.90552	-0.957	0.339366	
PoseStop sign:Condition_Order	0.04452	0.10744	411.83634	0.414	0.678832	
ConditionSigma:Poseexultation:Condition_Order	0.17057	0.15661	412.12535	1.089	0.276730	
ConditionSigma:Posephone:Condition_Order	0.08179	0.15391	411.91961	0.531	0.595423	
ConditionSigma:Poseputting hat on:Condition_Order	0.12194	0.15531	412.03575	0.785	0.432819	
ConditionSigma:PoseStop sign:Condition_Order	-0.01711	0.15299	411.87484	-0.112	0.910996	

Table A.3: Fixed Effects Results Hand Location

	Estimate	Std. Error	df	t value	Pr(> t)	
(Intercept)	1.11091	0.25517	58.91744	4.354	5.41e-05	***
ConditionSigma	-0.06706	0.27050	400.79712	-0.248	0.8043	
Poseexultation	-0.08449	0.27121	400.81587	-0.312	0.7556	
Posephone	0.01606	0.26655	400.83667	0.060	0.9520	
Poseputting hat on	0.10940	0.27426	400.92769	0.399	0.6902	
PoseStop sign	-0.06942	0.26676	400.77359	-0.260	0.7948	
Condition_Order	0.07890	0.16033	57.50094	0.492	0.6245	
Trial2	-0.03966	0.04704	401.45549	-0.843	0.3997	
Trial3	-0.11191	0.04693	401.34501	-2.384	0.0176	*
ConditionSigma:Poseexultation	-0.28313	0.37975	400.74848	-0.746	0.4564	
ConditionSigma:Posephone	-0.10599	0.37573	400.72757	-0.282	0.7780	
ConditionSigma:Poseputting hat on	-0.09844	0.38132	400.79950	-0.258	0.7964	
ConditionSigma:PoseStop sign	0.19431	0.37598	400.77190	0.517	0.6056	
ConditionSigma:Condition_Order	0.07826	0.17168	400.82095	0.456	0.6487	
Poseexultation:Condition_Order	0.08245	0.17279	400.85905	0.477	0.6335	
Posephone:Condition_Order	-0.15570	0.16804	400.82070	-0.927	0.3547	
Poseputting hat on:Condition_Order	-0.10766	0.17112	400.88202	-0.629	0.5296	
PoseStop sign:Condition_Order	-0.06343	0.17105	400.83720	-0.371	0.7110	
ConditionSigma:Poseexultation:Condition_Order	0.19006	0.24417	400.73586	0.778	0.4368	
ConditionSigma:Posephone:Condition_Order	0.03334	0.23805	400.69501	0.140	0.8887	
ConditionSigma:Poseputting hat on:Condition_Order	0.07521	0.24208	400.78829	0.311	0.7562	
ConditionSigma:PoseStop sign:Condition_Order	-0.05962	0.24032	400.87651	-0.248	0.8042	

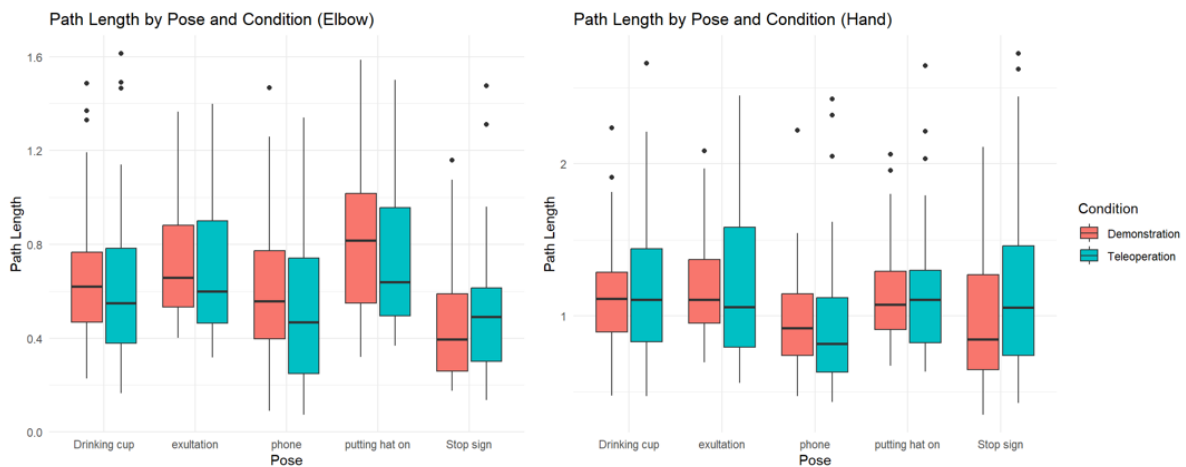


Figure A.2: Path Length per ADL Poses for Elbow and Hand Location

A.3. SPARC

Table A.4: Fixed Effects Results Elbow Location

	Estimate	Std. Error	df	t value	Pr(> t)	
(Intercept)	-4.4222	1.3412	86.1219	-3.297	0.00142	**
ConditionSigma	0.8583	1.5461	428.2016	0.555	0.57906	
Poseexultation	-1.3845	1.5326	428.1010	-0.903	0.36684	
Posephone	-3.5623	1.5461	428.2032	-2.304	0.02170	*
Poseputting hat on	-2.2782	1.5459	428.2007	-1.474	0.14130	
PoseStop sign	-1.9527	1.5360	428.0764	-1.271	0.20432	
Condition_Order	-1.3965	0.8421	83.9318	-1.658	0.10097	
Trial2	0.8218	0.2678	428.1805	3.069	0.00228	**
Trial3	0.8417	0.2674	428.1839	3.148	0.00176	**
ConditionSigma:Poseexultation	2.7203	2.1702	428.1261	1.253	0.21072	
ConditionSigma:Posephone	4.1480	2.1941	428.1450	1.890	0.05937	.
ConditionSigma:Poseputting hat on	2.1932	2.1745	428.1399	1.009	0.31374	
ConditionSigma:PoseStop sign	0.2033	2.1772	428.1290	0.093	0.92564	
ConditionSigma:Condition_Order	0.2237	0.9778	428.2006	0.229	0.81919	
Poseexultation:Condition_Order	0.8398	0.9725	428.1412	0.864	0.38830	
Posephone:Condition_Order	2.1828	0.9778	428.2048	2.232	0.02611	*
Poseputting hat on:Condition_Order	1.8275	0.9777	428.2007	1.869	0.06228	.
PoseStop sign:Condition_Order	1.1973	0.9779	428.0787	1.224	0.22146	
ConditionSigma:Poseexultation:Condition_Order	-1.4308	1.3796	428.1772	-1.037	0.30024	
ConditionSigma:Posephone:Condition_Order	-2.2721	1.3831	428.1438	-1.643	0.10115	
ConditionSigma:Poseputting hat on:Condition_Order	-1.6233	1.3753	428.1394	-1.180	0.23851	
ConditionSigma:PoseStop sign:Condition_Order	-0.1460	1.3792	428.1038	-0.106	0.91574	

Table A.5: Fixed Effects Results Hand Location

	Estimate	Std. Error	df	t value	Pr(> t)	
(Intercept)	-6.129115	1.343352	85.822367	-4.563	1.67e-05	***
ConditionSigma	2.701890	1.528548	433.162497	1.768	0.07783	.
Poseexultation	-0.016336	1.525017	433.135000	-0.011	0.99146	
Posephone	-0.188507	1.535360	433.249048	-0.123	0.90234	
Poseputting hat on	-1.829539	1.521855	433.151639	-1.202	0.22995	
PoseStop sign	-0.044558	1.525225	433.182241	-0.029	0.97671	
Condition_Order	-0.330012	0.846617	84.755818	-0.390	0.69766	
Trial2	0.541820	0.263146	433.130239	2.059	0.04009	*
Trial3	0.702239	0.263201	433.151278	2.668	0.00792	**
ConditionSigma:Poseexultation	2.375873	2.147154	433.098239	1.107	0.26911	
ConditionSigma:Posephone	-0.418540	2.161681	433.188413	-0.194	0.84657	
ConditionSigma:Poseputting hat on	2.286322	2.142593	433.100600	1.067	0.28653	
ConditionSigma:PoseStop sign	-2.342433	2.147156	433.098842	-1.091	0.27590	
ConditionSigma:Condition_Order	-1.168660	0.976523	433.205852	-1.197	0.23206	
Poseexultation:Condition_Order	0.008539	0.970960	433.137912	0.009	0.99299	
Posephone:Condition_Order	0.558819	0.971340	433.240001	0.575	0.56538	
Poseputting hat on:Condition_Order	1.719630	0.965963	433.178710	1.780	0.07574	.
PoseStop sign:Condition_Order	0.079998	0.971286	433.253971	0.082	0.93440	
ConditionSigma:Poseexultation:Condition_Order	-1.031244	1.369306	433.118320	-0.753	0.45179	
ConditionSigma:Posephone:Condition_Order	0.426722	1.369638	433.178189	0.312	0.75553	
ConditionSigma:Poseputting hat on:Condition_Order	-1.346577	1.362093	433.123571	-0.989	0.32341	
ConditionSigma:PoseStop sign:Condition_Order	1.924668	1.369258	433.118869	1.406	0.16055	

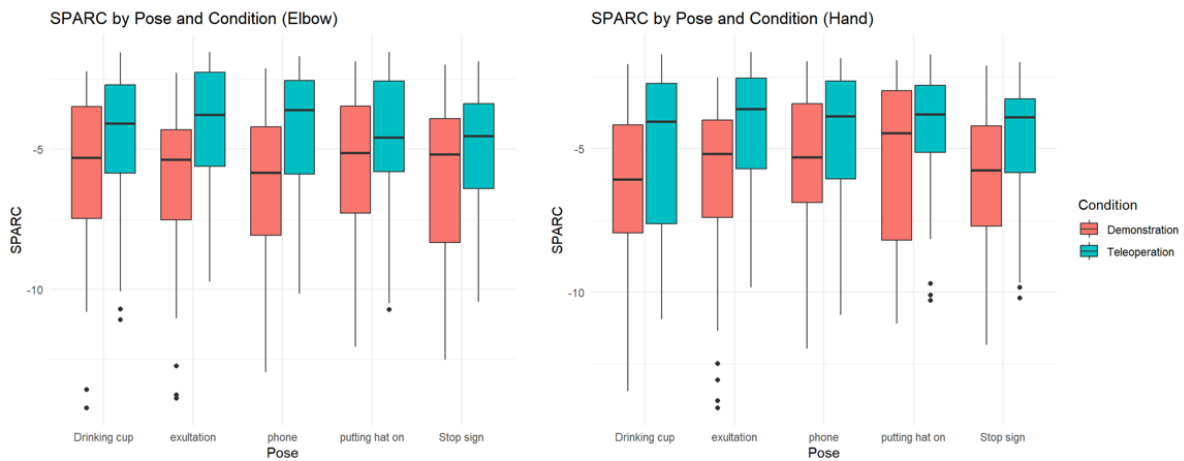


Figure A.3: SPARC per ADL Poses for Elbow and Hand Location

A.4. Questionnaire Data

A.4.1. Mean and Standard Deviation

Table A.6: Summary of Demands and Performance by Role and Condition

Role	Condition	Mental Demand		Physical Demand		Temporal Demand	
		Mean	SD	Mean	SD	Mean	SD
Leader	Demonstration	52.5	23.45	47.5	29.83	31.56	23
Leader	Teleoperation	48.12	24.49	41.88	25.36	33.12	24.42
Follower	Demonstration	22.5	14.94	55.31	18.66	20.62	14.36
Follower	Teleoperation	21.56	20.06	35	21.29	24.69	17.27
		Performance		Effort		Frustration	
		Mean	SD	Mean	SD	Mean	SD
Leader	Demonstration	74.69	20.29	60.62	24.07	22.5	27.39
Leader	Teleoperation	77.81	16.53	50.94	23.33	20.31	27.48
Follower	Demonstration	76.25	14.2	53.12	24.69	10.31	10.87
Follower	Teleoperation	73.44	15.57	24.69	20.2	12.19	9.3

Table A.7: Summary of IMI and SUS Scores by Condition and Role

Condition	Role	IMI – Perceived Competence		IMI - Effort		SUS	
		Demonstration	Teleoperation	Demonstration	Teleoperation	Demonstration	Teleoperation
Follower	Mean	70.83	70.14	73.33	57.92	65.62	67.19
	SD	13.92	18.20	20.72	15.32	12.42	11.92
Leader	Mean	66.49	76.39	78.33	74.79	71.41	71.25
	SD	19.97	18.27	20.06	20.65	14.17	18.71

A.4.2. Workload (RTLX)

Mental Demand

Table A.8: Summary of Fixed Effects

Term	Estimate	Std. Error	df	t value	Pr(> t)
(Intercept)	22.5000	5.2668	51.3562	4.272	8.39e-05 ***
RoleLeader	30.0000	7.4484	51.3562	4.028	0.000186 ***
ConditionTeleoperation	-0.9375	5.7200	30.0000	-0.164	0.870910
RoleLeader:ConditionTeleoperation	-3.4375	8.0893	30.0000	-0.425	0.673909

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table A.9: Summary of Contrast Estimates

Contrast	Estimate	SE	df	t.ratio	p.value
Follower Demonstration - Leader Demonstration	-30.000	7.45	51.4	-4.028	0.0010 **
Follower Demonstration - Follower Teleoperation	0.938	5.72	30.0	0.164	0.9984
Follower Demonstration - Leader Teleoperation	-25.625	7.45	51.4	-3.440	0.0062 **
Leader Demonstration - Follower Teleoperation	30.938	7.45	51.4	4.154	0.0007 ***
Leader Demonstration - Leader Teleoperation	4.375	5.72	30.0	0.765	0.8696
Follower Teleoperation - Leader Teleoperation	-26.562	7.45	51.4	-3.566	0.0043 **

Physical Demand

Table A.10: Summary of Fixed Effects

Term	Estimate	Std. Error	df	t value	Pr(> t)
(Intercept)	55.312	6.040	59.246	9.158	6e-13 ***
RoleLeader	-7.812	8.541	59.246	-0.915	0.3641
ConditionTeleoperation	-20.312	8.045	30.000	-2.525	0.0171 *
RoleLeader:ConditionTeleoperation	14.687	11.377	30.000	1.291	0.2066

Table A.11: Summary of Contrast Estimates

Contrast	Estimate	SE	df	t.ratio	p.value
Follower Demonstration - Leader Demonstration	7.81	8.54	59.2	0.915	0.7971
Follower Demonstration - Follower Teleoperation	20.31	8.05	30.0	2.525	0.0762
Follower Demonstration - Leader Teleoperation	13.44	8.54	59.2	1.573	0.4015
Leader Demonstration - Follower Teleoperation	12.50	8.54	59.2	1.463	0.4657
Leader Demonstration - Leader Teleoperation	5.62	8.05	30.0	0.699	0.8966
Follower Teleoperation - Leader Teleoperation	-6.88	8.54	59.2	-0.805	0.8519

Temporal Demand

Table A.12: Summary of Fixed Effects

Term	Estimate	Std. Error	df	t value	Pr(> t)
(Intercept)	20.625	5.046	43.193	4.087	0.000186 ***
RoleLeader	10.938	7.137	43.193	1.533	0.132669
ConditionTeleoperation	4.062	4.377	30.000	0.928	0.360764
RoleLeader:ConditionTeleoperation	-2.500	6.190	30.000	-0.404	0.689184

Table A.13: Summary of Contrast Estimates

Contrast	Estimate	SE	df	t.ratio	p.value
Follower Demonstration - Leader Demonstration	-10.94	7.14	43.2	-1.533	0.4274
Follower Demonstration - Follower Teleoperation	-4.06	4.38	30.0	-0.928	0.7901
Follower Demonstration - Leader Teleoperation	-12.50	7.14	43.2	-1.752	0.3104
Leader Demonstration - Follower Teleoperation	6.88	7.14	43.2	0.963	0.7708
Leader Demonstration - Leader Teleoperation	-1.56	4.38	30.0	-0.357	0.9841
Follower Teleoperation - Leader Teleoperation	-8.44	7.14	43.2	-1.182	0.6411

Performance

Table A.14: Summary of Fixed Effects

Term	Estimate	Std. Error	df	t value	Pr(> t)
(Intercept)	76.250	4.200	55.975	18.156	<2e-16 ***
RoleLeader	-1.562	5.939	55.975	-0.263	0.793
ConditionTeleoperation	-2.812	5.081	30.000	-0.554	0.584
RoleLeader:ConditionTeleoperation	5.937	7.186	30.000	0.826	0.415

Table A.15: Summary of Contrast Estimates

Contrast	Estimate	SE	df	t.ratio	p.value
Follower Demonstration - Leader Demonstration	1.56	5.94	56	0.263	0.9936
Follower Demonstration - Follower Teleoperation	2.81	5.08	30	0.554	0.9449
Follower Demonstration - Leader Teleoperation	-1.56	5.94	56	-0.263	0.9936
Leader Demonstration - Follower Teleoperation	1.25	5.94	56	0.210	0.9967
Leader Demonstration - Leader Teleoperation	-3.12	5.08	30	-0.615	0.9265
Follower Teleoperation - Leader Teleoperation	-4.38	5.94	56	-0.737	0.8819

Effort

Table A.16: Summary of Fixed Effects

Term	Estimate	Std. Error	df	t value	Pr(> t)
(Intercept)	53.125	5.784	58.762	9.184	5.86e-13 ***
RoleLeader	7.500	8.180	58.762	0.917	0.362987
ConditionTeleoperation	-28.437	7.564	30.000	-3.760	0.000736 ***
RoleLeader:ConditionTeleoperation	18.750	10.696	30.000	1.753	0.089831 .

Table A.17: Summary of Contrast Estimates

Contrast	Estimate	SE	df	t.ratio	p.value
Follower Demonstration - Leader Demonstration	-7.50	8.18	58.8	-0.917	0.7960
Follower Demonstration - Follower Teleoperation	28.44	7.56	30.0	3.760	0.0039 ***
Follower Demonstration - Leader Teleoperation	2.19	8.18	58.8	0.267	0.9932
Leader Demonstration - Follower Teleoperation	35.94	8.18	58.8	4.393	0.0003 ***
Leader Demonstration - Leader Teleoperation	9.69	7.56	30.0	1.281	0.5819
Follower Teleoperation - Leader Teleoperation	-26.25	8.18	58.8	-3.209	0.0113 **

Signif. codes: *** 0.001 ** 0.01 * 0.05 ' ' 0.1 ' ' 1

Frustration

Table A.18: Summary of Fixed Effects

Term	Estimate	Std. Error	df	t value	Pr(> t)
(Intercept)	10.312	5.169	60.000	1.995	0.0506
RoleLeader	12.188	7.309	60.000	1.667	0.1007
ConditionTeleoperation	1.875	7.309	60.000	0.257	0.7984
RoleLeader:ConditionTeleoperation	-4.062	10.337	60.000	-0.393	0.6957

Table A.19: Summary of Contrast Estimates

Contrast	Estimate	SE	df	t.ratio	p.value
Follower Demonstration - Leader Demonstration	-12.19	7.31	60	-1.667	0.3498
Follower Demonstration - Follower Teleoperation	-1.88	7.31	30	-0.257	0.9940
Follower Demonstration - Leader Teleoperation	-10.00	7.31	60	-1.368	0.5240
Leader Demonstration - Follower Teleoperation	10.31	7.31	60	1.411	0.4977
Leader Demonstration - Leader Teleoperation	2.19	7.31	30	0.299	0.9905
Follower Teleoperation - Leader Teleoperation	-8.12	7.31	60	-1.112	0.6839

A.4.3. Usability (SUS)

Table A.20: Summary of Fixed Effects

Term	Estimate	Std. Error	df	t value	Pr(> t)
(Intercept)	65.625	3.638	56.402	18.038	<2e-16 ***
RoleLeader	5.781	5.145	56.402	1.124	0.266
ConditionTeleoperation	1.562	4.093	32.000	0.382	0.705
RoleLeader:ConditionTeleoperation	-1.719	5.789	32.000	-0.297	0.768

Table A.21: Summary of Fixed Effects

Contrast	Estimate	SE	df	t.ratio	p.value
Follower Demonstration - Leader Demonstration	-5.781	5.31	60.2	-1.088	0.6982
Follower Demonstration - Follower Teleoperation	-1.562	4.23	34.1	-0.370	0.9825
Follower Demonstration - Leader Teleoperation	-5.625	5.31	60.2	-1.059	0.7158
Leader Demonstration - Follower Teleoperation	4.219	5.31	60.2	0.794	0.8569
Leader Demonstration - Leader Teleoperation	0.156	4.23	34.1	0.037	1.0000
Follower Teleoperation - Leader Teleoperation	-4.062	5.31	60.2	-0.764	0.8701

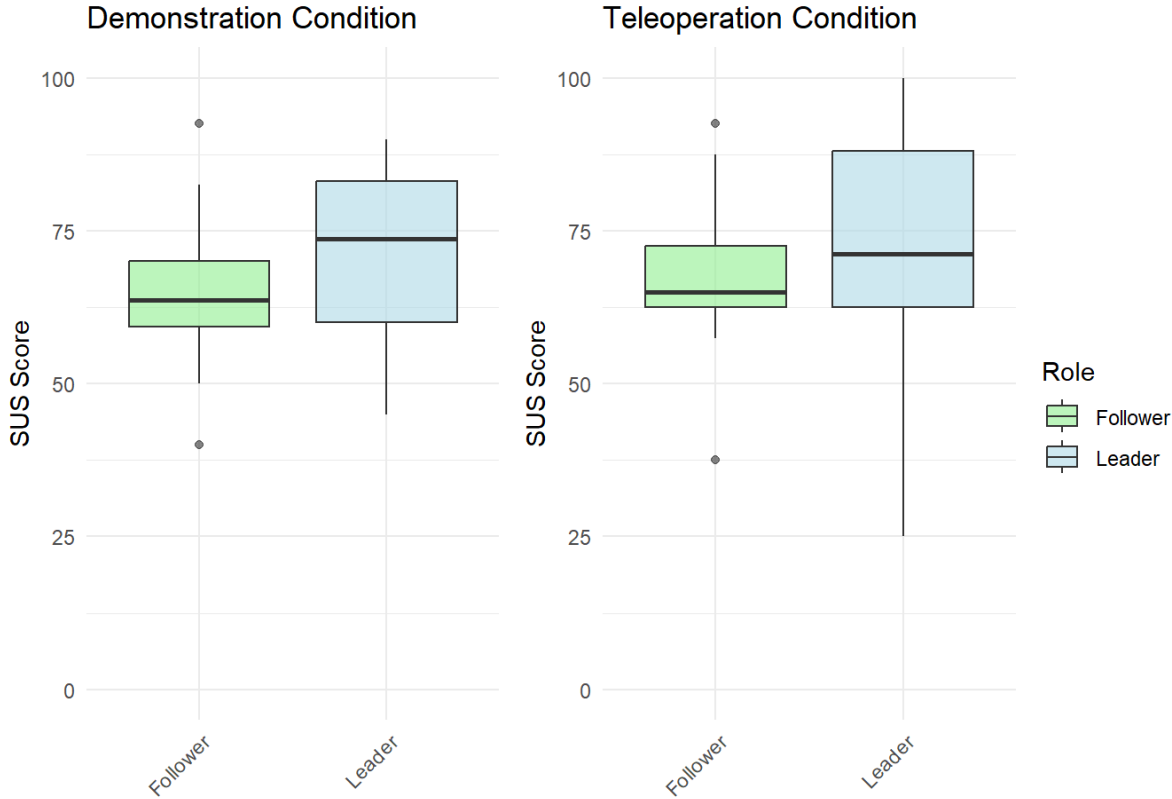


Figure A.4: SUS Results

A.4.4. Motivation (IMI)

Effort

Table A.22: Summary of Fixed Effects

Term	Estimate	Std. Error	df	t value	Pr(> t)
(Intercept)	73.333	4.640	42.792	15.805	<2e-16 ***
RoleLeader	5.000	6.562	42.792	0.762	0.4502
ConditionTeleoperation	-15.417	3.428	288.000	-4.498	9.98e-06 ***
RoleLeader:ConditionTeleoperation	11.875	4.848	288.000	2.450	0.0149 *

Table A.23: Summary of Fixed Effects

Contrast	Estimate	SE	df	t.ratio	p.value
Follower Demonstration - Leader Demonstration	-5.00	6.75	45.6	-0.741	0.8801
Follower Demonstration - Follower Teleoperation	15.42	3.44	290.0	4.482	0.0001
Follower Demonstration - Leader Teleoperation	-1.46	6.75	45.6	-0.216	0.9964
Leader Demonstration - Follower Teleoperation	20.42	6.75	45.6	3.024	0.0205
Leader Demonstration - Leader Teleoperation	3.54	3.44	290.0	1.030	0.7322
Follower Teleoperation - Leader Teleoperation	-16.88	6.75	45.6	-2.500	0.0734

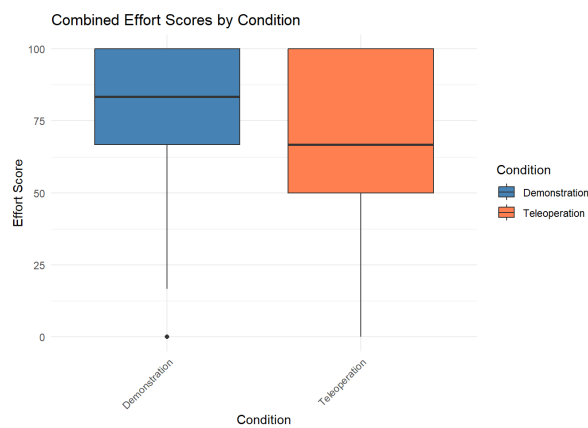


Figure A.5: IMI Effort Conditions

Perceived Competence

Table A.24: Summary of Fixed Effects

Term	Estimate	Std. Error	df	t value	Pr(> t)
(Intercept)	70.8333	4.0091	38.6719	17.668	<2e-16 ***
RoleLeader	-4.3403	5.6697	38.6719	-0.766	0.44861
ConditionTeleoperation	-0.6944	2.4156	352.0000	-0.287	0.77391
RoleLeader:ConditionTeleoperation	10.5903	3.4161	352.0000	3.100	0.00209 **

Table A.25: Summary of Contrasts in Fixed Effects

Contrast	Estimate	SE	df	t.ratio	p.value
Follower Demonstration - Leader Demonstration	4.340	5.84	41.2	0.743	0.8790
Follower Demonstration - Follower Teleoperation	0.694	2.42	354.0	0.287	0.9918
Follower Demonstration - Leader Teleoperation	-5.556	5.84	41.2	-0.951	0.7775
Leader Demonstration - Follower Teleoperation	-3.646	5.84	41.2	-0.624	0.9237
Leader Demonstration - Leader Teleoperation	-9.896	2.42	354.0	-4.085	0.0003
Follower Teleoperation - Leader Teleoperation	-6.250	5.84	41.2	-1.070	0.7094

B

Experiment

B.1. Experimental Procedure

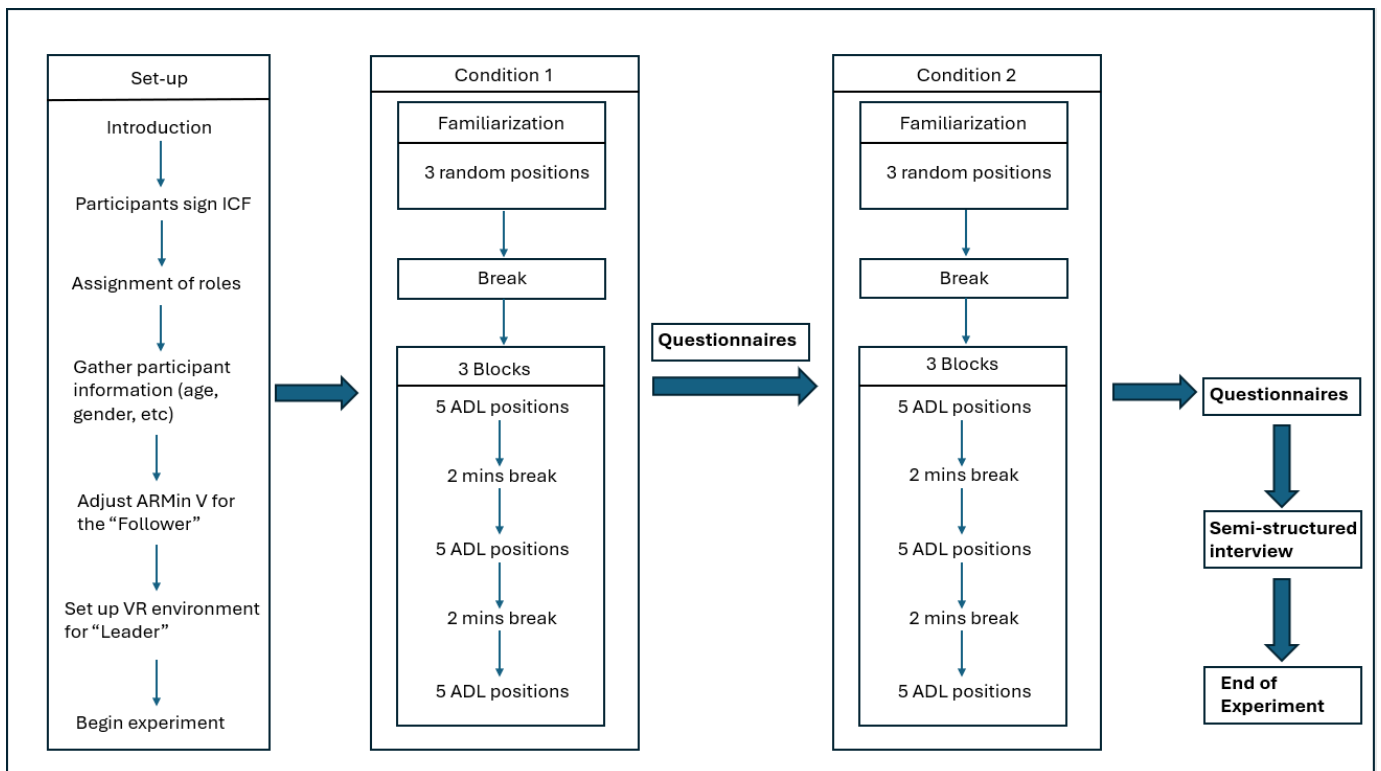


Figure B.1: Complete Experimental Procedure.

B.2. Poses

Table B.1: Joint angles for the ADL positions

Position	Joint 1	Joint 2	Joint 3	Joint 4	Joint 5	Joint 6
Base position	-106	-50	-51	67	142	4
Drinking cup	-163	-63	-13	96	104	-40
Stop sign	-88	-62	-10	46	103	-7
Exultation	-121	-111	-17	56	92	5
Putting hat on	-137	-98	-17	102	145	-18
Phone	-127	-61	-10	117	107	-20

Table B.2: Joint angles for random positions in the familiarization phase

Position	Joint 1	Joint 2	Joint 3	Joint 4	Joint 5	Joint 6
Random Position 1	-103	-98	-13	36	104	-40
Random Position 2	-100	-100	-10	46	103	-7
Random Position 3	-141	-70	-25	56	92	5

B.2.1. Base Position

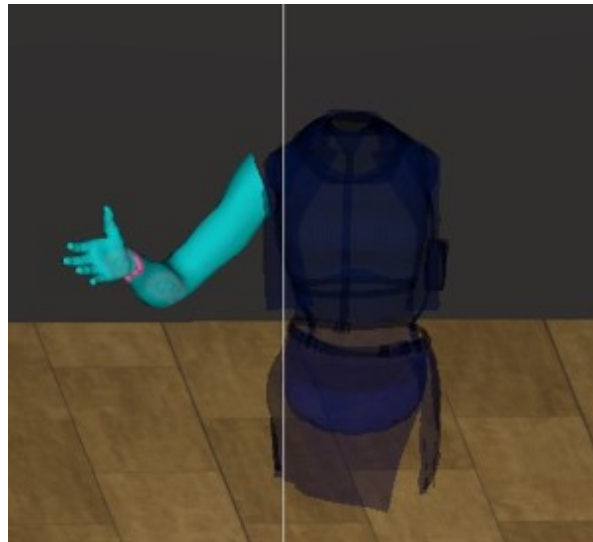


Figure B.2: Base Position.

C

VR Environment

C.0.1. Digital clone ARMin

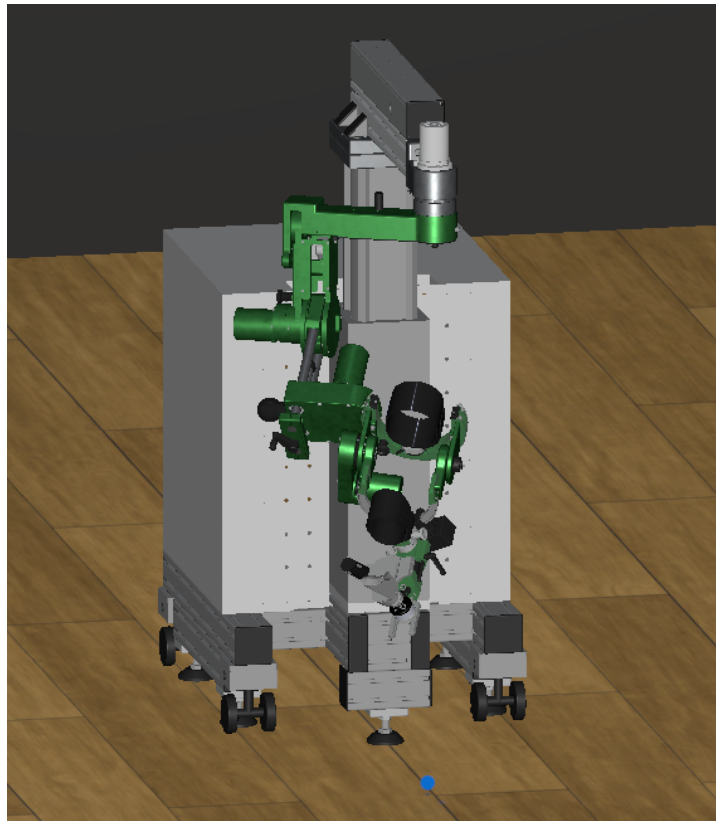


Figure C.1: Digital clone ARMin

C.0.2. VR arm

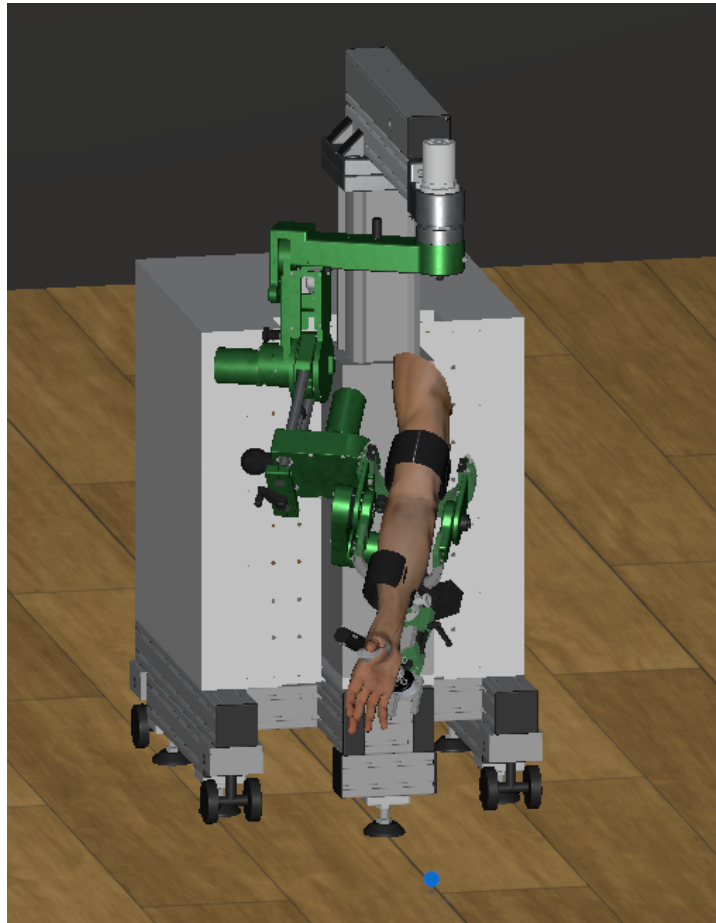


Figure C.2: VR arm

C.0.3. Female and Male torso

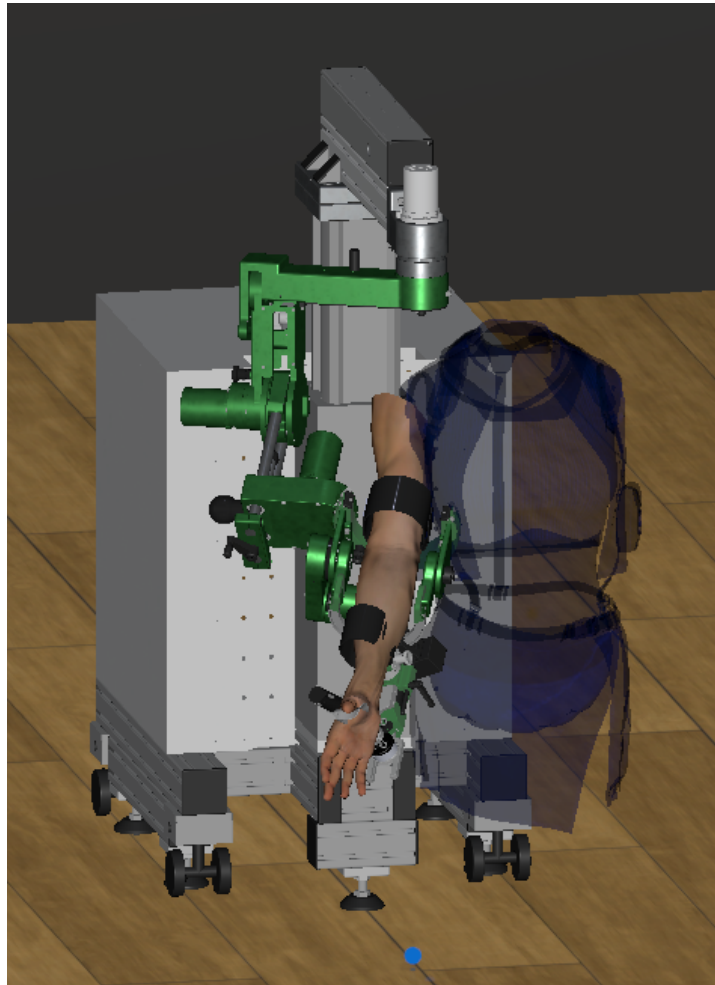


Figure C.3: Female torso

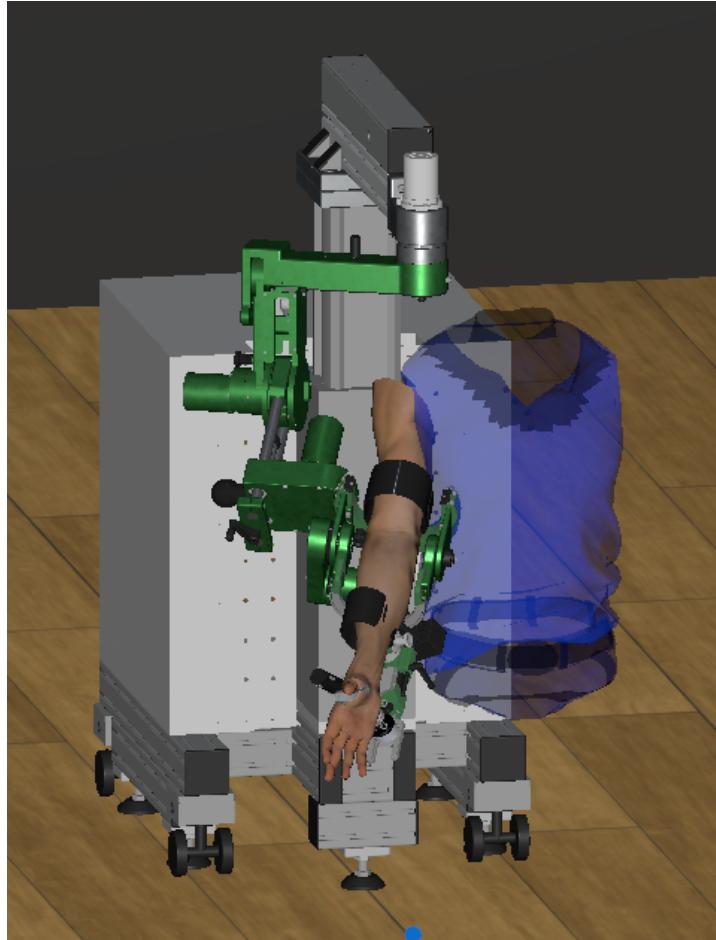


Figure C.4: Male torso

C.0.4. Experiment

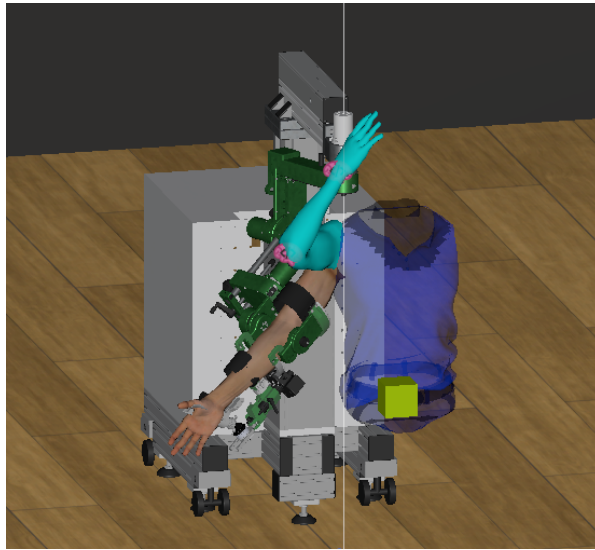


Figure C.5: Experiment: putting hat on pose is shown here

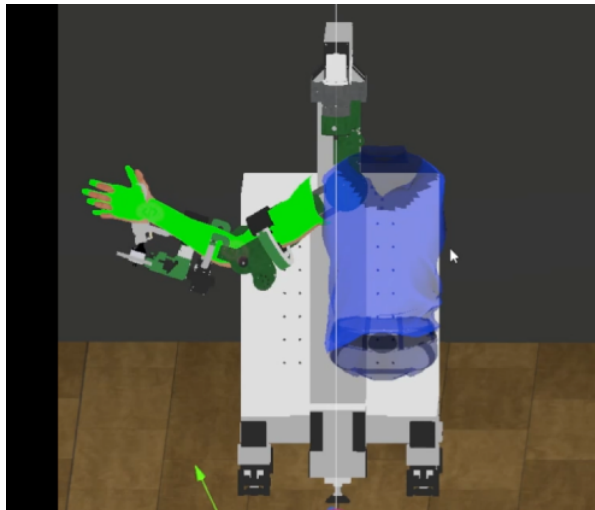


Figure C.6: Experiment: the target arm is green because the two arms are matching. The pose here is stop sign.

C.0.5. UXF

Startup

Local data save directory

Participant ID

Session number

Familiarization

Condition

Weight

Gender

Welcome to UXF!
You could use this space to display some instructions to the researcher or the participant.

Please tick if you understand the instructions and agree for your data to be collected and used for research purposes.*

Begin session

Figure C.7: UXF GUI

D

Simulink

D.0.1. Scope Board

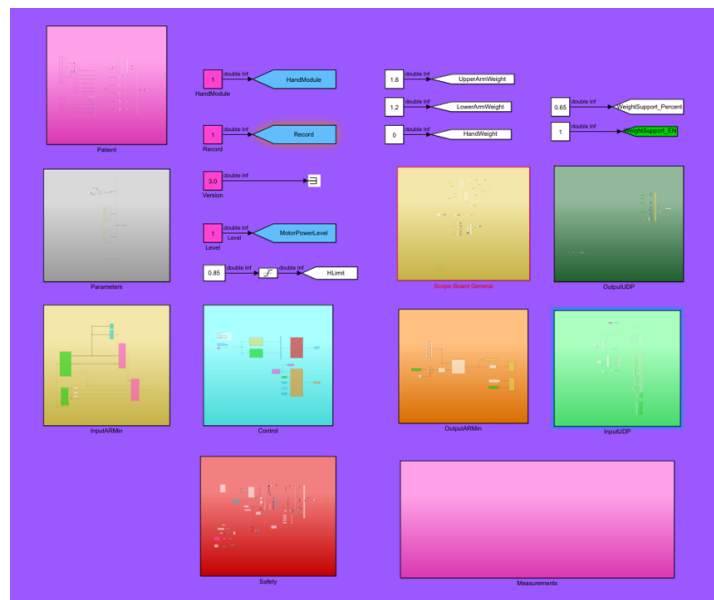


Figure D.1: Simulink - Scope Board

D.0.2. ARMin Control

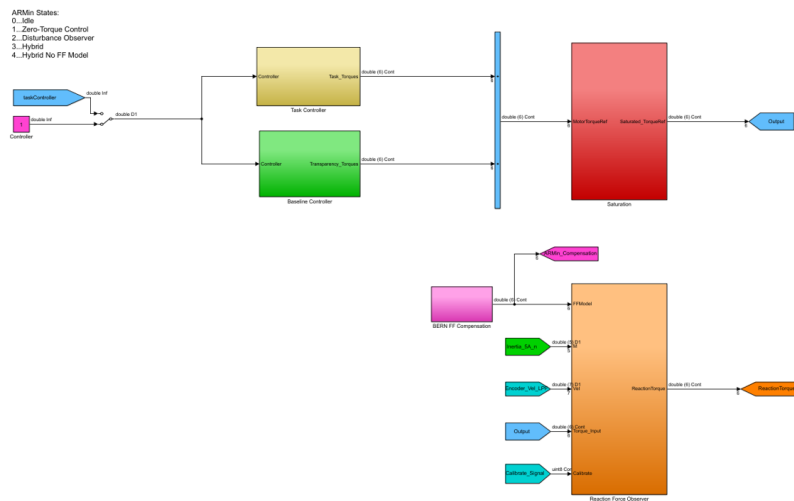


Figure D.2: Simulink - Controller

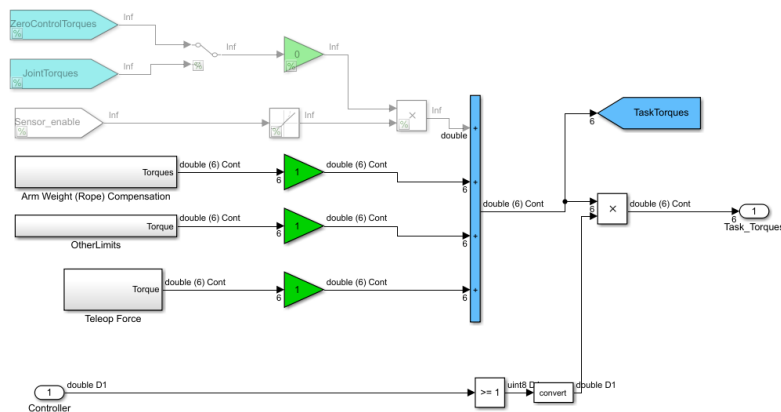


Figure D.3: Simulink - Task controller

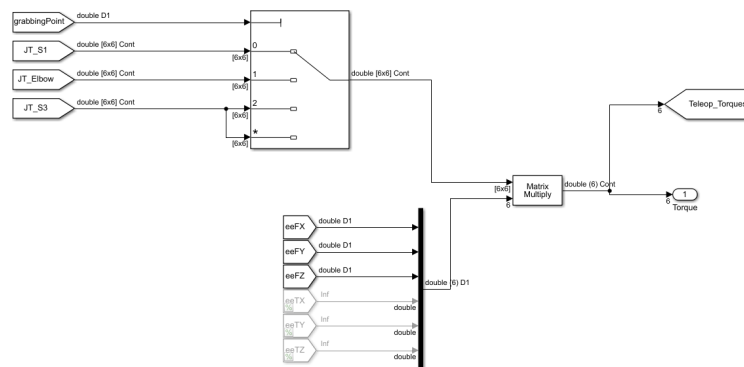


Figure D.4: Simulink - teleoperation forces multiplied by the Jacobian. The "grabbingpoint" indicates if the therapist has grabbed the elbow or wrist of the digital clone.

D.0.3. Arm Weight Compensation

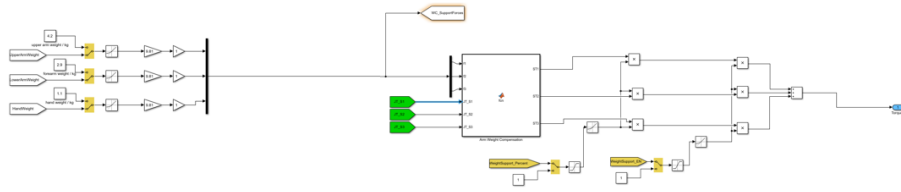


Figure D.5: Simulink - Arm Weight Compensation

E

Informed Consent Form

Delft University of Technology

**HUMAN RESEARCH ETHICS
INFORMED CONSENT**

Version 27/02/2024

Enhancing Communication in a Telerehabilitation Setting Using the Armin Exoskeleton through Combined Verbal and Haptic Feedback: An Experimental Study.

You are being invited to participate in a research study titled “Enhancing Communication in a Telerehabilitation Setting Using the Armin Exoskeleton through Combined Verbal and Haptic Feedback: An Experimental Study”. This study is being performed at the Motor Learning and Neurorehabilitation (MLN) Laboratory at the TU Delft, Cognitive Robotics Department.

The purpose of this study is to evaluate whether the telerehabilitation system can enhance communication between patient and therapist. The study will take approximately 80 minutes.

In this experiment, you will use either the ARMin exoskeleton or the Sigma.7, an end-effector haptic device. The robots will be operated in connected mode with each other. You will either be assigned the “follower” or the “leader” role. As the leader, your goal will be to communicate an arm position to the follower using the ARMin exoskeleton. The leader will be able to visualize the follower arm and the target arm configuration using a head-mounted display. The experiment will be repeated for two conditions: In the first condition, the leader will be able to communicate the target arm position using verbal communication and physical demonstrations. In the second condition, the leader will be able to communicate the target arm position using verbal communication and by moving the follower’s arm using the Sigma.7.

An experimenter will always be present and you will receive specific instructions before the experiment.

During the experiment, we will record movement and performance data, as well as record the communication between the two participants using an audio recorder. The audio will be stored on TU Delft servers and will not be published. At the end of each condition, participants will be asked to fill out questionnaires. At the end of the experiment, a semi-structured interview will take place to discuss the experience.

Because the device that you will test is not CE certified, it cannot be excluded that a failure or malfunction occurs, which could potentially result in discomfort. Otherwise, no physical, emotional, or reputational risks are expected. Although the haptic forces that you will experience during the experiment are low, risks of minor injury during the interaction with the robot have been mitigated by following safety procedures in accordance with the TU Delft safety protocol.

During the experiment, you may experience minor muscular fatigue or discomfort in your arm, mitigated by several pauses between trials. There is a risk of Covid-19 transmission through equipment surfaces or face-to-face encounters, mitigated by disinfection of the robot. Additionally, your personal data and your answers will remain confidential and we will pseudo-anonymize your collected data prior to the publication of the study.

Your participation in this study is entirely voluntary and you can withdraw at any time during the experiment. You are free to omit any questions. You have the right to request access to and/or deletion

of your collected data until one month after your participation, before the publication of the study. In case of any questions or requests, contact:

Matti Lang – Msc Student (M.A.Lang@student.tudelft.nl)

Alex Ratschat – Daily Supervisor (A.L.Ratschat@tudelft.nl)

Alex van den Berg – Daily Supervisor (A.vandenBerg-2@tudelft.nl)

Dr. Laura Marchal-Crespo – Supervisor (L.MarchalCrespo@tudelft.nl)

Explicit Consent Points

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICIPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information dated <i>27/02/2024</i> , or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	<input type="checkbox"/>	<input type="checkbox"/>
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	<input type="checkbox"/>	<input type="checkbox"/>
3. I understand that taking part in the study involves: <ul style="list-style-type: none"> • I will receive instructions about the tasks and the systems that I will test • I will perform tasks with the Exoskeleton or Haptic device. The experimenter will always be present and I will receive specific instructions prior to the experiment but will be asked to perform the tasks by myself. • A computer monitor or head-mounted display will be used to display a task that has to be performed with the device. • The device is capable of generating haptic forces at the interaction point with the arm. While performing the tasks, I will feel the interaction forces through the device. 	<input type="checkbox"/>	<input type="checkbox"/>
4. I understand that there will be no compensation for my participation	<input type="checkbox"/>	<input type="checkbox"/>
5. I understand that the study will take approximately 80 minutes	<input type="checkbox"/>	<input type="checkbox"/>
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
6. I understand that taking part in the study involves the following risks: <ul style="list-style-type: none"> • The Exoskeleton that is part of the system is a research prototype and not a CE-certified device. It can therefore not be excluded that a mechanical or electrical failure or a software malfunction occurs with a risk of minor discomfort, pain or injury. • I may experience minor fatigue or discomfort in the arm during the tasks • I may experience exposure to COVID-19 I understand that these will be mitigated by:	<input type="checkbox"/>	<input type="checkbox"/>

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
<ul style="list-style-type: none"> • An in-depth risk assessment was performed by the developers and the risks of injury were mitigated in accordance with the TU Delft protocol. For instance, the device is equipped with an emergency stop and a Deadman's Switch. Pressing the emergency stop or releasing the Deadman's Switch immediately cuts power to the device. • Appropriate resting time is assigned between trials and I am always allowed to press the emergency stop button at any time without justification. • All equipment will be disinfected before and after use. All relevant Covid-19 regulations and recommendations of the Dutch government during the time of the experiment will be complied with. 		
<p>7. I understand that taking part in the study also involves collecting specific personally identifiable information (PII) such as name, age, weight and contact details and associated personally identifiable research data (PIRD) with the potential risk of my identity being revealed to all researchers involved in this study. No PII or PIRD will be made publicly available.</p>	<input type="checkbox"/>	<input type="checkbox"/>
<p>8. I understand that some of this PIRD are considered sensitive data within GDPR legislation, specifically</p> <ul style="list-style-type: none"> • All data will be stored according to a data management plan that was developed and approved by an expert at TU Delft. • The collected data will be stored on a server located at the TU Delft. • The collected data will be pseudonymized. • The informed consent sheet will be stored on a server located at the TU Delft. 	<input type="checkbox"/>	<input type="checkbox"/>
<p>9. I understand that the following steps will be taken to minimize the threat of a data breach and protect my identity in the event of such a breach.</p> <ul style="list-style-type: none"> - Data will be pseudonymized. - Data will be stored on a server at the TU Delft - Audio files will be encrypted 	<input type="checkbox"/>	<input type="checkbox"/>
<p><i>Provide brief summaries of the mitigating measures to be taken (eg: anonymous data collection, (pseudo-) anonymisation or aggregation, secure data storage/limited access, transcription, blurring, voice modification etc)</i></p>		
<p>10. I understand that personal information collected about me that can identify me, such as my name or age, will not be shared beyond the study team.</p>	<input type="checkbox"/>	<input type="checkbox"/>
<p>11. I understand that the (identifiable) personal data I provide will be destroyed after publication of the study results.</p>	<input type="checkbox"/>	<input type="checkbox"/>

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
12. I understand that after the research study the de-identified information I provide will be used for further development of the device, report(s), publication(s), presentation(s), and teaching	<input type="checkbox"/>	<input type="checkbox"/>
D: (LONGTERM) DATA STORAGE, ACCESS AND REUSE		
13. I give permission for the de-identified research data (e.g. task metrics, age) that I provide to be archived in 4TU Data Center repository and the Zenodo repository so it can be used for future research and learning.	<input type="checkbox"/>	<input type="checkbox"/>
14. I understand that access to this repository is open	<input type="checkbox"/>	<input type="checkbox"/>

Signatures		
_____	_____	_____
Name of participant [printed]	Signature	Date
<p>I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.</p>		
_____	_____	_____
Matti Lang	Signature	Date
Study contact details for further information: [<i>Name, phone number, email address</i>]		
Matti Lang		
+33670852573		
m.a.lang@student.tudelft.nl		

F

Qualtrics Survey

Question Tour Block 1

Welcome!

Please answer the following questions.

Participant Number

Name

Age

Sex assigned at birth

- Male
- Female
- Other (specify)
-

Is English your mother tongue?

- Yes
- No (specify)
-

What is your English level?

- A1 - Beginner
- A2 - Elementary
- B1 - Pre-intermediate

- B2 - Intermediate
 - C1 - Upper-intermediate
 - C2 - Advanced
 - C3 - Native speaker
-

Handedness

- Right-handedness
 - Left-handedness
 - Ambidexterious
-

Do you have previous experience with Immersive Virtual Reality?

- Never used
 - Used once or twice
 - Used occasionally (a few times a year)
 - Used frequently (several times a month)
 - Used very frequently
-

Do you have experience with the Sigma.7?

- Never used
 - Used once or twice
 - Used occasionally (a few times a year)
 - Used frequently (several times a month)
 - Used very frequently
-

Do you have experience with the ARMin Exoskeleton?

- Never used
- Used once or twice
- Used occasionally (a few times a year)
- Used frequently (several times a month)
- Used very frequently

Which role were you assigned for the experiment?

- Leader
- Follower

Thank you for your answers! We are now going to start with the experiment.

Intrinsic Motivation Inventory (IMI) - Perceived Competence

	1 - Not at all true	2	3	4 - Somewhat true	5	6	7 - Very true
I think I am pretty good at this activity	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I think I did pretty well at this activity, compared to other students	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
After working at this activity for a while, I felt pretty competent	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I am satisfied with my performance at this task	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I was pretty skilled at this activity	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
This was an activity that I couldn't do very well	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Intrinsic Motivation Inventory (IMI) - Effort

	1 - Not at all true	2	3	4 - Somewhat true	5	6	7 - Very true
I put a lot of effort into this	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I didn't try very hard to do well at this activity	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

	1 - Not at all true	2	3	4 - Somewhat true	5	6	7 - Very true
I tried very hard on this activity	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
It was important to me to do well at this task	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I didn't put much energy into this	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

NASA Task Load Index

	Very Low 0	Very high 20
Mental Demand: How mentally demanding was the task?	<input type="range"/>	
Physical Demand: How physically demanding was the task?	<input type="range"/>	
Temporal Demand: How hurried or rushed was the pace of the task?	<input type="range"/>	
Performance: How successful were you in accomplishing what you were asked to do?	<input type="range"/>	
Effort: How hard did you have to work to accomplish your level of performance?	<input type="range"/>	
Frustration: How insecure, discouraged, irritated, stressed, and annoyed were you?	<input type="range"/>	



System Usability Scale (SUS)

System = communication system

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
I think that I would like to use this system frequently	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I found the system unnecessarily complex	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I thought the system was easy to use	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I think that I would need the support of a technical person to be able to use this sytem	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I found the various functions in this system were well integrated	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I thought there was too much inconsistency in this system	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I would imagine that most people would learn to use this system very quickly	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I found the system very cumbersome to use	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I felt very confident using the system	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I needed to learn a lot of things before I could get going with this sytem	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Thank you for your answers! The second block will now start.

Question Tour Block 2

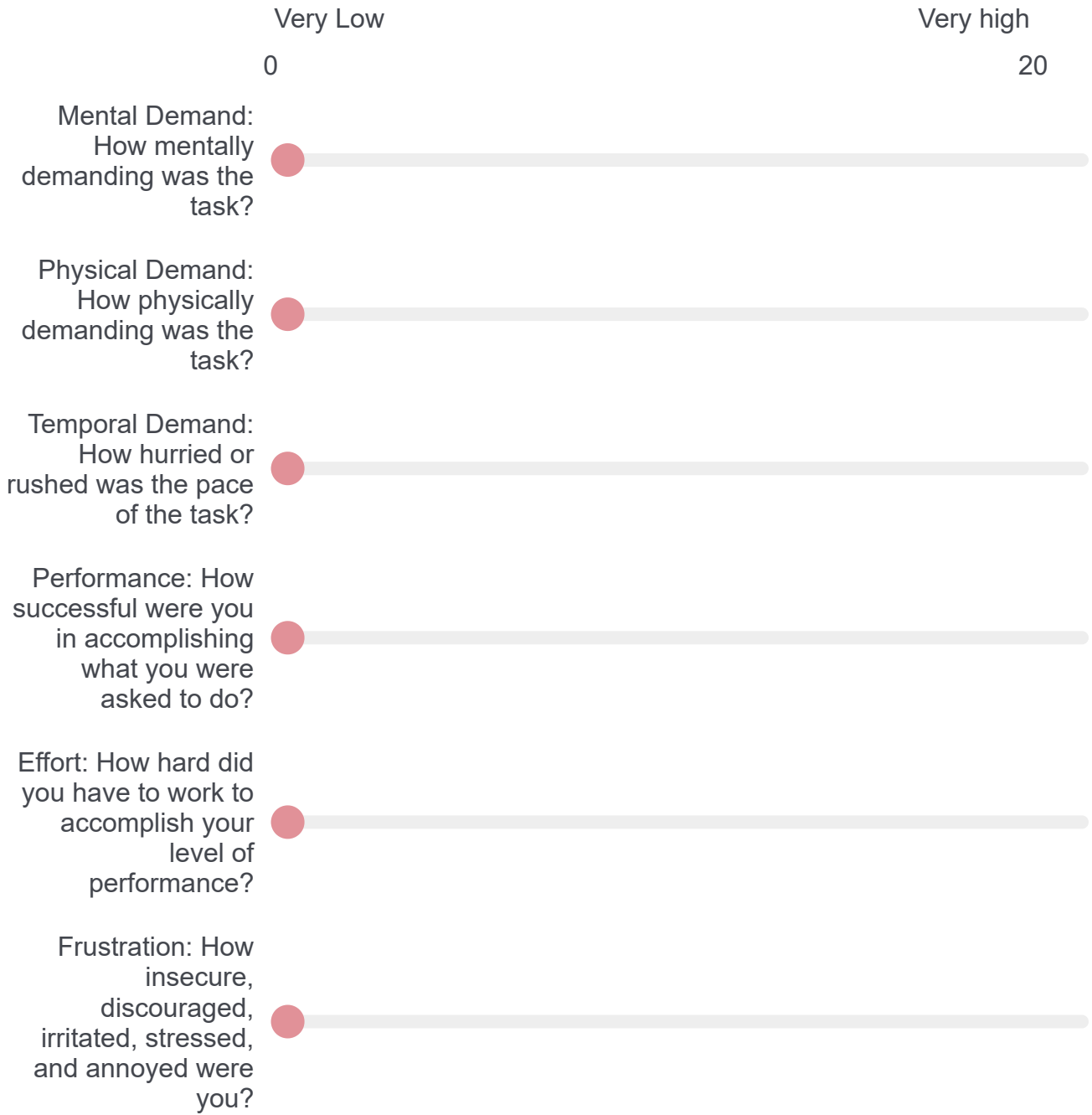
Intrinsic Motivation Inventory (IMI) - Perceived Competence

	1 - Not at all true	2	3	4 - Somewhat true	5	6	7 - Very true
I think I am pretty good at this activity	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I think I did pretty well at this activity, compared to other students	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
After working at this activity for a while, I felt pretty competent	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I am satisfied with my performance at this task	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I was pretty skilled at this activity	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
This was an activity that I couldn't do very well	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Intrinsic Motivation Inventory (IMI) - Effort

	1 - Not at all true	2	3	4 - Somewhat true	5	6	7 - Very true
I put a lot of effort into this	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I didn't try very hard to do well at this activity	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I tried very hard on this activity	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
It was important to me to do well at this task	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I didn't put much energy into this	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

NASA Task Load Index



System Usability Scale (SUS)

System = communication system

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
I think that I would like to use this system frequently	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I found the system unnecessarily complex	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I thought the system was easy to use	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
I think that I would need the support of a technical person to be able to use this sytem	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I found the various functions in this system were well integrated	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I thought there was too much inconsistency in this system	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I would imagine that most people would learn to use this system very quickly	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I found the system very cumbersome to use	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I felt very confident using the system	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I needed to learn a lot of things before I could get going with this sytem	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Question Tour Block 3

Submit questionnaire

- Yes
- No

Powered by Qualtrics

