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ORIGINAL ARTICLE

Augmented reality for upper limb rehabilitation: real-time kinematic feedback with HoloLens 2

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Abstract

Exoskeletons for rehabilitation can help enhance motor recovery in individuals suffering from neurological disorders. Precision in movement execution, especially in arm rehabilitation, is crucial to prevent maladaptive plasticity. However, current exoskeletons, while providing arm support, often lack the necessary 3D feedback capabilities to show how well rehabilitation exercises are being performed. This reduces therapist acceptance and patients' performance. Augmented Reality technologies offer promising solutions for feedback and gaming systems in rehabilitation. In this work, we leverage HoloLens 2 with its advanced hand-tracking system to develop an application for personalized rehabilitation. Our application generates custom holographic trajectories based on existing databases or therapists' demonstrations, represented as 3D tunnels. Such trajectories can be superimposed on the real training environment. They serve as a guide to the users and, thanks to colour-coded real-time feedback, indicate their performance. To assess the efficacy of the application in improving kinematic precision, we conducted a feasibility study with 15 healthy subjects. Comparing user tracking capabilities with and without the use of our feedback system in executing 4 different exercises, we observed significant differences, demonstrating that our application leads to improved kinematic performance. 12 clinicians tested our system and positively evaluated its usability (System Usability Scale score of 67.7) and acceptability (4.4 out of 5 in the 'Willingness to Use' category in the relative Technology Acceptance Model). The results from the tests on healthy participants and the feedback from clinicians encourage further exploration of our framework, to verify its potential in supporting arm rehabilitation for individuals with neurological disorders.

Keywords Augmented reality · Robotic rehabilitation · Kinematic feedback · Hand-tracking · HoloLens

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1 Introduction

Executing effective rehabilitation exercises is essential for people suffering from the motor consequences of neurological disorders to regain their lost abilities (Takeuchi and Izumi 2013). The physiological execution of movements reduces their metabolic cost and increases their efficiency. Moreover, performing motor tasks accurately, according to the therapist's specific plan to enhance the activation of the correct muscles and synergies, is fundamental to obtaining positive rehabilitation outcomes and avoiding the occurrence of maladaptive plasticity phenomena (Takeuchi and Izumi 2013). During standard rehabilitation, therapists assist, guide and support their patients in executing such tasks, ensuring they are performed correctly. Augmented feedback on patient performance, often provided by therapists, plays a pivotal role in supplementing the intrinsic feedback that patients typically lack following a traumatic event, such as a stroke (Thikey et al. 2012). This feedback, in real-time, ensures the accurate execution of movements, which is vital for successful recovery.

1.1 The importance of visual feedback

When coming to technologically-aided rehabilitation, feedback on the patient's performance can be provided in different ways including visual, auditory, haptic or multimodal. Visual is the most investigated modality and its efficacy has been demonstrated, especially for complex tasks (Sigrist et al. 2013). Due to the peculiar complexity of physiological arm movements, visual feedback is particularly effective in enhancing patients' upper-limb kinematic performance and can provide task or trajectory guidance through displays, headsets, or projectors (Sigrist et al. 2013). It encourages a precise kinematic execution of the task, improving performances (Thikey et al. 2012), but it can also help the therapist understand and monitor the condition of their patients.

Specific applications of visual feedback include mirror visual feedback, which can help improve the control abilities and coordination in post-stroke patients through visualisation of the contralateral arm (Urra et al. 2015; Kim et al. 2023). Representations of abstract variables indicating patients' performances, such as bar plots indicating inter-limb displacement (Maslovat et al. 2009) or force plots showing how close the subject is to the target in manual exercises (Snodgrass et al. 2010), can help patients adjust and refine their motor behaviour. Tables with embedded LEDs or monitors can guide to reach target positions during rehabilitation tasks (Dalla Gasperina et al. 2023) or inform about how precisely the patient is executing the movement (Simonsen et al. 2017). While these methods offer many advantages, they often lack the three-dimensionality essential for representing complex arm movements, which is fundamental to representing the complexity of multidimensional arm movements (Sigrist et al. 2013).

1.2 Current challenges and potential of virtual reality

Virtual Reality (VR)-based systems can offer an effective solution (Debnath et al. 2021). Making the patient observe a screen with a concurrent virtual reproduction of the task they are executing, such as ball-hitting with a racket (Todorov et al. 1997), is an efficient option to train specific motor gestures. Headset applications can offer a more immersive 3D experience, as seen in systems like the one described by Semblantes et al. (2018), which tracks and reproduces patients' gestures in a virtual environment and delivers terminal feedback by comparing them with gestures executed by therapists. VR frameworks can also assist clinicians in supervising robotic rehabilitation sessions. In fact, therapists and doctors lose perception of the condition of the treated limb when patients wear robotic devices, which strongly reduces the acceptability level towards rehabilitation technologies (Laparidou et al. 2021; Luciani et al. 2023). The system proposed by Quintana et al. (2022) merges virtual reality games for rehabilitation with an interface for real-time supervision of the patient, designed to help the therapist better gain insight into the rehabilitation process. Despite all the advantages represented by VR systems for rehabilitation, they carry some disadvantages. Immersive VR headsets, for example, may cause dizziness and nausea in some people (Saredakis et al. 2020; Simón Vicente et al. 2022) due to the total isolation from the external world and the consequent discrepancies between what the users see and what they perceive with the other senses. Moreover, VR systems do not provide chances for interaction with the real environment or object manipulation (Alamri et al. 2010), limiting the chances for translation of rehabilitation exercises into activities of daily living.

1.3 Augmented reality for upper-limb rehabilitation

Augmented Reality (AR) systems can provide an effective answer to these limitations, taking augmented visual feedback a step further. AR integrates virtual objects with the real environment surrounding the user, guaranteeing a heightened feeling of embodiment (Genay et al. 2021) and leaving the chance of interacting with objects. AR has demonstrated its potential in offering visual feedback and supporting patients during arm training (Phan et al. 2022). Patients can follow virtual objects' guidance, receiving

precise feedback on task execution (Sigrist et al. 2013; Phan et al. 2022).

de Crignis et al. (2023) demonstrated the feasibility of the application of serious AR games in clinical environments. They tested a 3D puzzle that consisted of constructing a house with some bricks collecting positive feedback from both therapists and patients. The work presented by Burke et al. (2010) implemented different AR applications that utilise physical markers to enable the interaction of real-world objects, such as a cube, within a virtual environment. Such screen-based applications included a brick-breaker game and a task-oriented game where the user has to move the cube in different required locations. The AR system evaluates the marker position and indicates if the exercises are performed correctly. Assis et al. (2014) proposed an innovative application that uses a virtual arm on the screen to replace an impaired limb for people undergoing post-stroke rehabilitation therapy, to help them gain shoulder range of motion/movement. They demonstrated that the integration of their game into post-stroke rehabilitation therapy improved the outcomes of the treatment. Desai et al. (2016) used the Microsoft Kinect V2 to implement AR-based exergames projecting the participant in virtual environments.

Virtual objects can provide accurate feedback to the patients, enhancing their participation in the rehabilitation sessions (Sigrist et al. 2013; Phan et al. 2022). AR can be used to measure the speed and direction of upper-limb movements and to provide feedback about the patient's capability to adapt and avoid obstacles (Bank et al. 2018) or to execute specific poses (Escalona et al. 2020). These indications are of key importance also for the therapist supervising the training sessions.

From all these examples we can see how AR has the potential to support and inform rehabilitation sessions in an effective and engaging way. While Kinect and screen-based systems offer advantages like cost-effectiveness and easy setups, headset-based applications have been often preferred, even by elderly people, as they increase the feeling of involvement in the exercise (Jordan and King 2011). Headsets guarantee an immersive, portable, and precise experience with real-time feedback, as well as opportunities for unrestricted movement.

Fig. 1 HoloLens 2 Headset (Microsoft 2024)

1.4 Contribution of our work

Despite the presence of different AR applications for rehabilitation, to the best of our knowledge, no previous work implemented an AR-based feedback system for 3D tracking of the hand of the user during custom rehabilitation exercises, with real-time performance indication. To address these gaps, in this paper, we present an AR rehabilitation system designed to provide 3D guidance to the users on trajectories to be executed during training sessions and to evaluate, in real time, their kinematic performances.

Our feedback system, developed for HoloLens 2 by Microsoft, projects holograms of prerecorded trajectories and tracks users' hand movements. The holograms are superimposed onto the real clinical or home environment, providing precise indications for the patient to follow and still allowing for real-object interaction. Our system's real-time hand-tracking feature includes a colour-coded indication of the user's precision in following the trajectory, with three different dimensions representing distinct confidence intervals. We tested our system in a feasibility study with 15 healthy individuals to demonstrate that, with the AR system, they can execute the exercises with higher accuracy. Participants performed tests with 4 different exercises with specific trajectories, always wearing the upper-limb exoskeleton AGREE to be used as a reliable hand-tracking system, recording the real-time positions of the arm of the user. Additionally, 12 clinicians from a neurorehabilitation centre in Milan evaluated our system in terms of usability and acceptability according to its capacity to fulfil their need for improved kinematic feedback about the patient during rehabilitation sessions, especially when a robotic device is involved.

In other words, with this work, our aim has been to:

- Develop an AR system to provide precise 3D feedback;
- Demonstrate its feasibility in improving patients' kinematic accuracy in the execution of rehabilitation exercises;
- Verify its effectiveness in informing both patient and therapist about the patient's abilities when exercising.

2 Materials

2.1 HoloLens 2 and correlated tools

The HoloLens 2 headset (Microsoft, Washington, USA), depicted in Fig. 1, projects virtual images onto a screen

through prisms and optical systems, precisely directing the images over an appropriately expanded area (Microsoft 2024). In such a way, the wearer of the headset sees the virtual objects superimposed on the real environment. The interaction between the user and the virtual space is made possible through the hand-tracking algorithm provided by the headset itself, which recognizes the location of the hand and its segments in a referenced space. The hand-tracking enables the execution of various actions such as pinching or clicking. HoloLens 2 is equipped with numerous sensors, such as Inertial Measurement Units (IMUs), infrared and RGB cameras and depth-sensing cameras. It is completely wireless and weighs only 556 g. The operating system is a trimmed-down and adapted version of Windows 10 for virtual inputs and includes a comprehensive and open-source development environment (Microsoft 2024).

To realise custom holograms for HoloLens and program our virtual application, we employed the cross-platform game engine Unity, by Unity Technologies (Unity 2024). We integrated several external libraries to enhance the Unity environment with specific functionalities, such as:

- *Windows Mixed Reality* (WMR), to make the Unity development environment compatible with the HoloLens and handle interactions between hands and three-dimensional objects within the scene.
- *Tuberenderer* by "Sixth sensor" (Unity Asset Store 2024), to enable the creation of tubes around complex and nonlinear objects and create our custom trajectories.

Unity programming language is $C\#$, and the developer platform we used is Visual Studio. Also, Shapr3D, a 3D CAD software, was employed to create complex 3D models and then import them into the Unity environment (Shapr3D 2024).

2.2 AGREE

For this work, we needed a reliable arm-tracking system, to evaluate the kinematics of the different joints and the hand of the users while executing rehabilitation exercises, both with and without the use of the headset. The AGREE exoskeleton (Dalla Gasperina et al. 2023), with its relative encoders, provides real-time indication of the angular position of its joints (running with a 5 kHz sampling frequency). Thanks to the robot's kinematic model, the end-effector's position is then easily calculated. AGREE is a four-degrees-of-freedom upper-limb exoskeleton by Politecnico di Milano, designed to assist subjects suffering from motor deficits caused by neurological disorders in their rehabilitation process, that has been validated as a reliable assessment tool for arm functioning (Longatelli et al. 2023). Using AGREE as an evaluation tool for kinematic performance, while using our application, also offers the chance to test the AR framework in a realistic condition of use within a robotic rehabilitation session.

3 Methods: implementation of the application and testing

3.1 Application structure

The application we developed for HoloLens 2 has been thought to include three main phases:

3.1.1 Calibration

This phase is needed to establish a correspondence between the virtual local reference system and the real workspace. It is crucial to ensure that the user can execute the tasks with the correct spatial feedback. It is thought to be executed by a technician or therapist, to avoid any fatiguing gesture for the patient. The implemented method employs the hand-tracking algorithm of HoloLens to locate three reference points, defining a plane, in space. When the calibration begins:

- A white sphere appears on the tip of the left-hand index finger of the user to indicate the virtual marker that needs to be fixed;
- The user can move the left hand and point the index finger with the sphere in the location they prefer;
- Clicking the "place" button that is present on the scene with the right hand, the user can fix the marker's position and the white sphere turns green.

These three steps need to be repeated three times to build a Cartesian reference and the working plane. We always used a table to help us in the definition of the reference plane. The whole procedure is represented in Fig. 2.

At the end of the Calibration phase, the therapist is offered the possibility of recording a new custom trajectory. Employing the cameras of the headset, our system can track and record the movements of the hand of the clinicians and create trajectories to be then proposed to the patients.

3.1.2 Trajectory selection and manipulation

This phase allows the visualisation of the trajectories and their manipulation in the space. Once the calibration is completed, the patient can wear the headset and sit in front of the table where the virtual workspace has been located. The trajectories to be used for the rehabilitation session are displayed in front of the user, on the virtual plane. As seen in

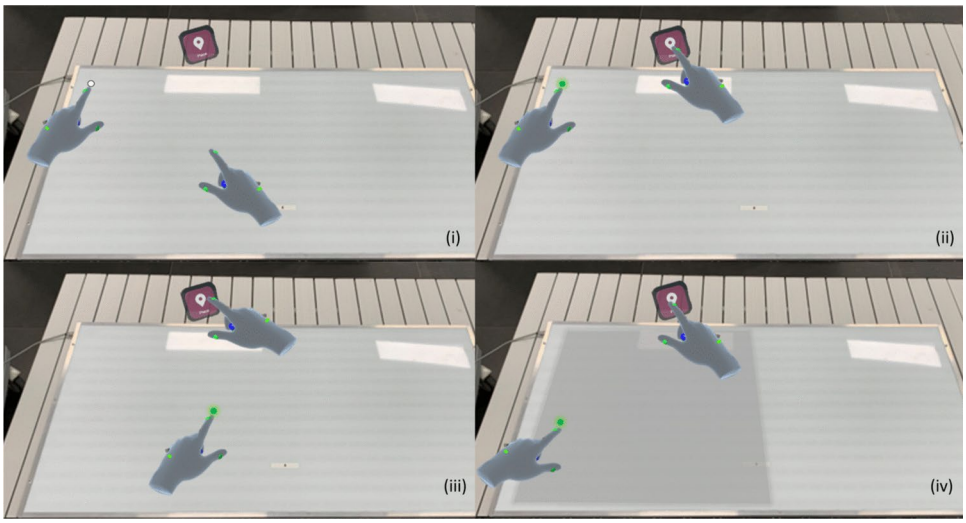

Fig. 2 Representation of the calibration procedure: **i** A white sphere appears and the user can locate it where they prefer, **ii** Pressing the *Place* button, the sphere turns green and keeps its position, indicating the first reference point, **iii** A second reference point is located in the same way, **iv** After the third point is located, the relative plane appears in the space

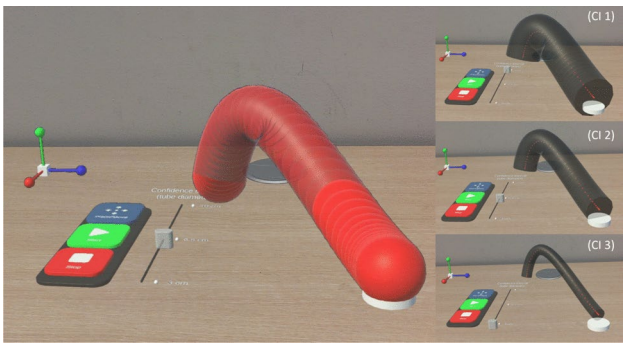

Fig. 3 Trajectories superimposed to the real environment. (LEFT) The appearance of a trajectory tunnel before the beginning of the execution, with the functioning buttons and the slider. The tunnel appears completely red before the user starts moving. (RIGHT) The pictures show the appearance of the trajectory with the three confidence intervals (CIs)

Fig. 3, each trajectory has a white base, that can be clicked to select the trajectory, and a series of three associated buttons and a slider.

The blue *Place/Move* button can be selected to move the trajectory. By clicking it with the left hand, the user can then use the right hand to move the base of the trajectory and locate it in correspondence to the desired starting point. A second click is needed to fix such a position and disable the motion. Since the horizontal plane has been defined during the calibration, the movement of the trajectory is allowed only along the coordinates of such plane but will keep the vertical position fixed at the level of the plane. The slider, positioned to the right of the buttons, is needed to select the desired confidence interval (CI) for the trajectory. We have three possible trajectory diameters (10–6.5–3 cm), representing how precise we want the user to be while executing the task. A CI of 10 cm means that we allow the patient to deviate from the desired trajectory for a maximum of 5 cm without giving them any negative feedback. With a CI of 3 cm, on the other side, we require them to be as precise as possible and will identify as an error any deviation that is bigger than 1.5 cm from the centre of the tunnel. The appearance of a trajectory with different CIs can be seen in Fig. 3. The green *Start* button has to be clicked at the beginning of the execution of the task. The trajectory changes its appearance and results as composed of red spheres with a diameter that coincides with the selected CI. The red *Stop* button, finally, needs to be clicked at the end of the exercise. For patients unable to control the contralateral arm, the buttons can be selected by the therapists via a computer that communicates to the HoloLens through its Holographic Remoting application.

3.1.3 Execution and scoring

Once the *Start* button has been clicked, the user can execute the task trying to follow the visual feedback represented by the trajectory. While they move their hand, the HoloLens tracking system instantaneously computes the position of the centroid of the hand and compares it to the position of the closest via-point of the trajectory. The distance is defined as a simple Euclidean difference. The spheres composing the trajectory change their appearance in real time, modifying their size according to the computed error. They "deflate" and change colour proportionally to the proximity between the hand and the trajectory's centre: the smaller the error, the smaller and the greener the sphere. If the error is bigger than the CI, the spheres remain red. If the centroid crosses exactly the desired path, the spheres are the smallest possible and coloured in dark green. We developed two options for the real-time error feedback system. With the first one, the feedback can be "overwritten" during every repetition of the movement, so that the user can notice the improvements by seeing the spheres scaling down. With the second option, the trajectory returns completely red after

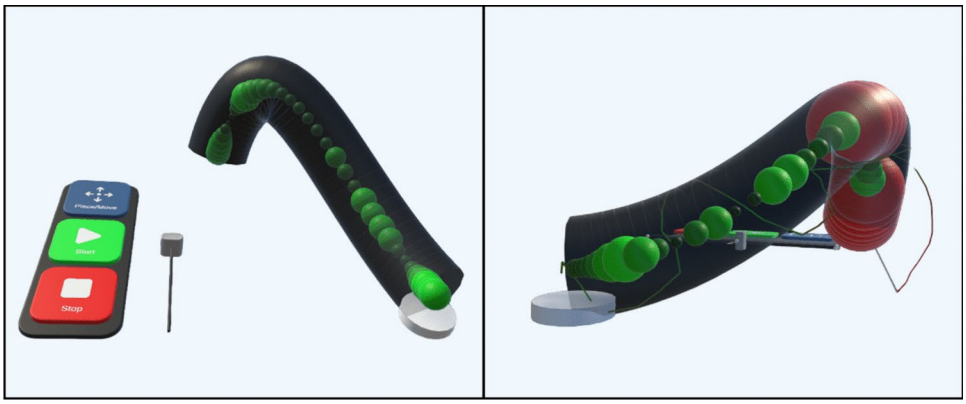

Fig. 4 Feedback system showing the error-based feedback system. (LEFT) The spheres have different sizes and colours according to the error in their specific position along the trajectory. (RIGHT) At the end of the task, the system provides a snapshot of the movements executed, represented by a line that tracks the whole path of the hand

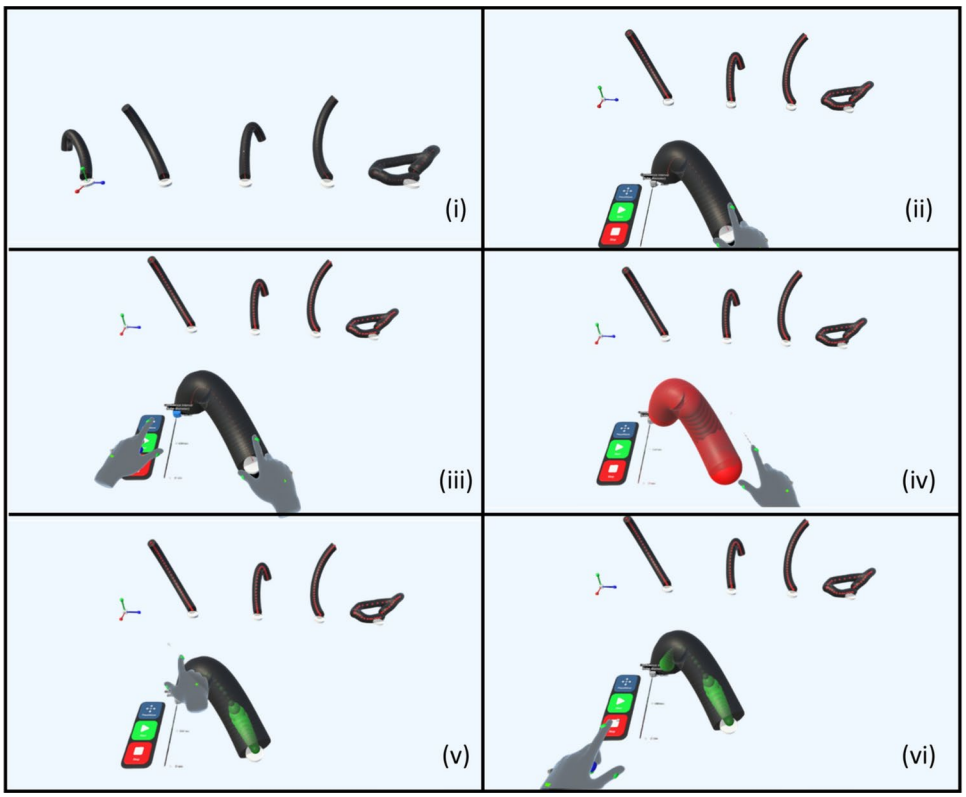

Fig. 5 Steps to follow to execute a task with the HoloLens feedback: **i** Select the trajectory from the options; **ii** Position the trajectory on the Start Point using the blue button; **iii** Start the exercise with the Green button; **iv** Start moving trying to keep the hand in the red tunnel; **v** Execute the trajectory: the tunnel turns green if the execution is correct; **vi** Press the red button to stop

every repetition. In Fig. 4 we can appreciate what happens during the execution of the task, thanks to the real-time error feedback system. In the left picture, we can appreciate the different sizes and colours of the spheres. The right picture represents what is visible after the end of the task execution. The thin coloured line represents the actual path followed by the user.

Figure 5 summarizes the steps to be followed by the user for a single trajectory and one CI.

3.2 Testing protocol: efficacy with healthy subjects

To evaluate the efficacy of our system in enhancing trajectory-tracking capabilities, we designed a feasibility study in accordance with the CONSORT 2010 extension for pilot and feasibility trials (Eldridge et al. 2016). The sample size for participants in the trial was set to 15, following literature recommendations for achieving meaningful initial statistical estimates (Julious 2005). The 15 participants were recruited (between November 2022 and March 2023) among healthy adults, with no history of neurological disorders and complete arm function (detailed demographic information is reported in Table 1).

For the experiments, we asked them to sit wearing AGREE and the HoloLens 2 on their head. In front of the subject, we positioned a table with some targets on it, at different height levels. Figure 6 shows the experimental setup.

At the beginning of each subject's session, they were instructed about the use of the two systems and they had a moment to familiarize themselves with the use of AR.

Table 1 Demographic information about the healthy participants of the study

	S.1	S.2	S.3	S.4	S.5	S.6	S.7	S.8	S.9	S.10	S.11	S.12	S.13	S.14	S.15
Age	32	26	27	25	27	25	26	27	27	24	26	25	27	28	25
Gender	M	M	F	M	M	M	F	M	F	F	M	M	M	M	F

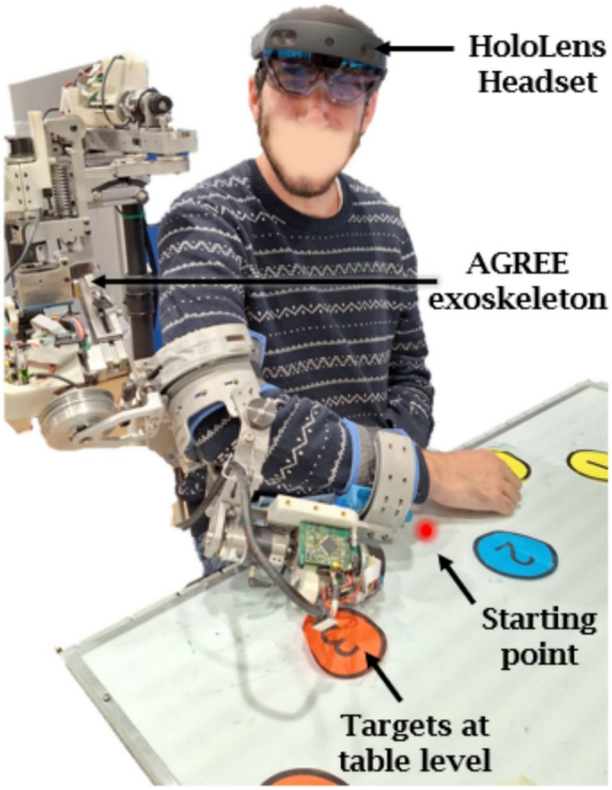

Fig. 6 Experimental setup with a subject wearing both the exoskeleton AGREE and the headset. In front of the subject, we have a table with targets to be used as reference points for the tasks

Before asking for their active participation, we executed the calibration phase (wearing the HoloLens only) and defined the starting point for the first trajectory. The exercises proposed to the users, developed to be proposed during rehabilitation sessions, were four: (T1) Reaching a point at the table level towards the left of the subject; (T2) Reaching a point at the shoulder level towards the left of the subject; (T3) Reaching a point at the shoulder level towards the front of the subject; (T4) Draw a clockwise circle at table level, starting from the starting point. The participants to the experiments signed an informed declaration of consent and the tests were approved by the Ethical Committee of Politecnico di Milano (approval n. 8/2022 - 16/02/2022).

3.2.1 Exercises execution

For each exercise, participants were initially instructed about the movement to be executed. They were then asked to follow some steps and repeat the exercise in different conditions.

Without wearing the headset:

- Perform the movement back and forth, having as references just the start and end points of the trajectory;

- Repeat the movement five times.

Wearing the HoloLens 2:

- Select the correct hologram for the trajectory to be executed from the virtual environment;
- Perform the corresponding movement back and forth, selecting the bigger confidence interval (C1);
- Perform the corresponding movement back and forth, selecting the medium confidence interval (C2);
- Perform the corresponding movement back and forth, selecting the smaller confidence interval (C3).

The order of application of the different exercise conditions was randomised to avoid the influence of any learning effect on the global results.

3.2.2 Error evaluation

To guarantee the repeatability of the results, comparing the kinematic error both with and without the use of HoloLens, our participants always wore AGREE. AGREE records the real-time joint positions of the four joints and, from them, the end-effector position is computed. At the end of each exercise, the five repetitions are isolated and normalised in time to be compared with the desired trajectory, which is stored in the trajectory generation system of AGREE (Gasperina et al. 2022). For every time sample i_th of each repetition, the formula used to evaluate the kinematic error in the end-effector space uses the root mean squared error (RMSE):

$$RMSE^i = \sqrt{(x^i - x_d^i)^2 + (y^i - y_d^i)^2 + (z^i - z_d^i)^2} \tag{1}$$

where x^i, y^i, z^i are the actual positions along the analysed repetition, while x_d^i, y_d^i, z_d^i are the desired ones. The error is then mediated over the single repetition, and over the five repetitions, giving the final result:

$$ERR_s^{T_j} = \frac{1}{N}\sum_{n=1}^{N}\left(\frac{1}{I}\sum_{i=1}^{I} RMSE^{i,n}\right) \tag{2}$$

where s is the participant analysed, T_j is the exercise, I is the total number of time samples for the normalised repetitions and N is the number of repetitions (5). In joint space, the error is first evaluated joint by joint and then averaged. This is repeated for every subject and exercise.

The errors have been gathered per exercise and then, globally, per confidence interval. We statistically analysed them to compare the results obtained with HoloLens, distinguishing the three CIs, with those obtained without the visual feedback guaranteed by our AR system. First, we checked the non-parametricity of our data distributions using the Kolmogorov-Smirnov test. We then created a generalized linear mixed (GLM) model with two factors—Exercise and Condition—with four levels each (T1, T2, T3 and T4 for Exercise; without HoloLens, C1, C2 and C3 for Condition) to highlight the effects of these factors on the error. The model considers Exercise and Conditions as fixed effects and includes participants as a random effect. After identifying significant effects, we used the Wilcoxon signed-rank test to compare the errors obtained in the various conditions. All statistical analyses were done using MATLAB 2022b.

Due to the intrinsic kinematic redundancy of the human arm, it is possible to move the hand along the same trajectory while positioning the elbow and shoulder joints in different configurations. To confirm that our end-effector-based feedback system does not lead to joint misalignments or introduce increased errors in joint space, the analyses and comparisons performed for the error in the end-effector space, were then repeated for all the joints.

3.2.3 Questionnaire

At the end of the protocol, the participants were asked to complete a questionnaire (see Appendix A). The questionnaire reported 22 sentences, regarding the intuitiveness and usability of our application. The sentences were classified into five categories: (i) Clarity of the calibration; (ii) Usability of the trajectory manipulation mechanism; (iii) Effectiveness of the guiding interface; (iv) Reliability and stability of the hand-tracking system (v) Comfort of the device. The volunteers had to indicate their degree of agreement with a score on a Likert scale from 1 (strongly disagree) to 5 (strongly agree).

3.3 Therapists' acceptability and usability evaluation

We presented our system to 12 professionals working in the neurorehabilitation clinic *Casa di Cura Igea S.p.A.*, in Milan. After a 30-minute session of training and testing of the device, we asked them to complete two questionnaires (see Appendix B) and evaluate the system in terms of usability (with a System Usability Scale - SUS) and acceptability (through the creation of a Technology Acceptance Model-AM). During the tests, they experimented with different trajectories and confidence intervals, replicating the experimental iterations proposed to the healthy subjects. Additionally, they tested the various button functionalities and tried out the additional option that we developed for the

therapist's side, which allowed them to record trajectories in real-time from demonstrations using their hands. Table 2 reports some personal information about the professionals involved (such as age, gender, profession, years of experience working in the rehabilitation field and attitude towards technology on a scale from 1 to 5).

For the usability part, we presented the 10 classical questions of a SUS evaluation (Bangor et al. 2008). After the completion of the questionnaire, we calculated the SUS score, for every participant, consistently with the literature. A score of 100 represents the best possible usability, while 68 indicates the threshold for an acceptable usability level. To inspect the acceptability of the system, we presented 21 questions, divided into 6 categories, and evaluated the answers to build a TAM (Marangunić and Granić 2015). We considered the three classic TAM categories (*Willingness To Use* (WTU), *Perceived Usefulness* (PU), *Perceived Ease of Use* (PEOU)) but also included three additional categories specifically referred to our system features (*Importance of Tridimensionality* (TRI), *Importance of therapy independence* (IND), *Importance of Graphical aspects* (GRAPH)). After the evaluation of Cronbach's alpha over the collected answers, two questions were eliminated (one for WTU and the other for GRAPH). The correlation between the different categories' results was examined by calculating the Pearson correlation coefficients and constructing a multiple linear regression model to connect the categories.

Table 2 Registry information about the participants to the evaluation

	Age	Gender	Profession	Years of Work	Attitude Towards Technology (/5)
S.1	32	M	PH	4	5
S.2	26	F	OT	2	3.25
S.3	34	F	PH	10	4.5
S.4	24	M	OT	4	4.5
S.5	32	F	PH	10	4.25
S.6	37	M	OT	15	3.75
S.7	37	F	PH	14	4
S.8	37	F	OT	14	3.25
S.9	31	F	BIO	4	5
S.10	33	M	PH	9	5
S.11	31	M	PH	5	3.25
S.12	41	M	PH	16	4.5

OT, occupational therapist; PH, physiotherapist; BIO, clinical bioengineer. The field Attitude Towards Technology reports the mean value of the scores (on a scale of 1–5) they attributed to 4 sentences indicating their level of interest and confidence when dealing with new technologies and with technology in their everyday life

4 Results

4.1 Efficacy with healthy subjects

4.1.1 Error analysis results

Table 3, displays the mean error computed for all the exercises without and with the HoloLens, for all the CIs and exercises. It also presents the global results (both mean and standard deviation of the error), obtained by averaging the errors across the four different exercises (i.e., T1, T2, T3, T4). The analysis of the generalised linear mixed model indicates that both the type of exercise executed (factor Exercise) and the condition for execution (factor Condition) have a significant effect on the error ($p_{value} < 0.05$). On the other side, the effect of the interaction between the two factors is not significant (undefined$p_{value} > 0.05$ 0.05]]>). This suggests that the difference in scores between conditions is consistent across different exercises. Since we are concentrating on the differences in errors when using our application versus not using it, and we have determined that the tasks do not affect these variations, the statistical evaluation using the Wilcoxon signed-rank test indicated in Table 3 focuses on the comparison between the *No Hololens* condition and the other three.

4.1.2 Questionnaire results

Table 4 reports the mean and standard deviations of the scores assigned to each of the categories analysed.

Table 3 Error summary, both in joint and end-effector space, for all the feedback modalities applied for the tests (without HoloLens, with HoloLens in the three CIs)

	End-effector space [cm]					Joint space [deg]				
	T1	T2	T3	T4	Global result	T1	T2	T3	T4	Global result
No Holo	2.46	2.43	2.24	1.97	2.28 ± 0.45	9.38	11.34	10.30	7.32	9.58 ± 0.86
Holo C1	2.23	2.28	2.11	1.63**	2.06 ± 0.57***	8.03**	10.63*	9.80	5.62**	8.52 ± 1.11***
Holo C2	2.19*	2.22*	2.16	1.66**	2.06 ± 0.59***	8.29**	10.09*	9.39*	6.01**	8.44 ± 1.30***
Holo C3	2.19*	2.33	2.14	1.68**	2.09 ± 0.56***	8.34*	10.29**	9.03**	5.86**	8.38± 1.20***

*, 0.05-significance; **, 0.01-significance; ***, 0.001-significance levels in the difference between the kinematic error and the results when no HoloLens was used

Table 4 Questionnaire results: mean and standard deviation of the scores for each category, on a scale from 1 (strongly disagree) to 5 (strongly agree)

Category	Score
Clarity of the calibration	4.04 ± 0.62
Usability of the trajectory manipulation mechanism	4.13 ± 0.23
Effectiveness of the guiding interface	4.57 ± 0.37
Reliability and stability of the hand-tracking system	3.57 ± 0.79
Comfort of the device	4.45 ± 0.44

4.2 Therapists' SUS and TAM results

Figure 7 represents the usability score distribution in the SUS scale. Our system gained a final SUS evaluation of 67.7 ± 12.1 out of 100. The results of the TAM analysis were mediated after converting the negative items to the proper scale. The mean scores gained by the 6 categories of the TAM model and a colour-based summary of the correlation between each category and the main WTU category are represented in Fig. 8.

Concerning the TAM generated from our questionnaires, we can see how the WTU and PU categories both obtained a mean score of 4.38 out of 5. The Perceived Ease of Use is slightly lower (3.50 out of 5) but has a lower correlation with the Willingness to Use the system (correlation index of 0.42) than the Perceived Usefulness (correlation index of 0.86). From the answers we collected,

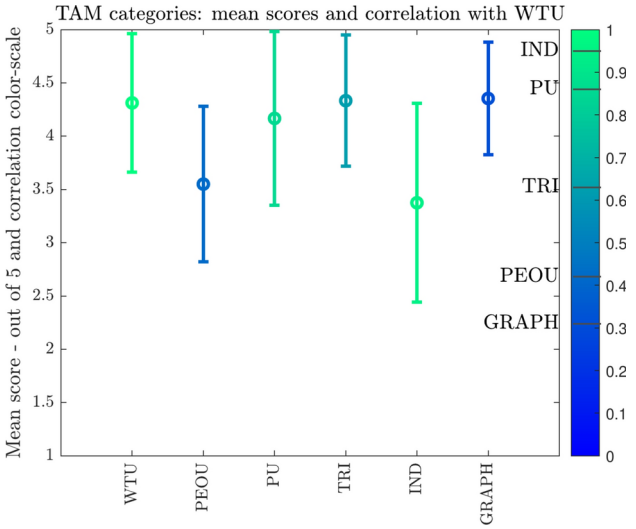

Fig. 8 Statistics of the scores (mean and standard deviation) gained by the 6 categories of the TAM model, with a colour-based summary of the correlation between each category and the main WTU category

we developed a multiple-regression model to measure the effect of the different variables on the WTU. We considered PU and PEOU to have a direct impact on WTU, while TRI, GRAPH and IND affect the Perceived Usefulness. With a significance level of 0.01, we obtained the following model: $WTU = 0.73 * PU + 0.35 * PEOU$, where $PU = 0.59 * TRI + 0.50 * IND$. *GRAPH* did not have a significant effect on *PU*. The *WTU* scores attributed by the participants and their Attitude Towards Technology are

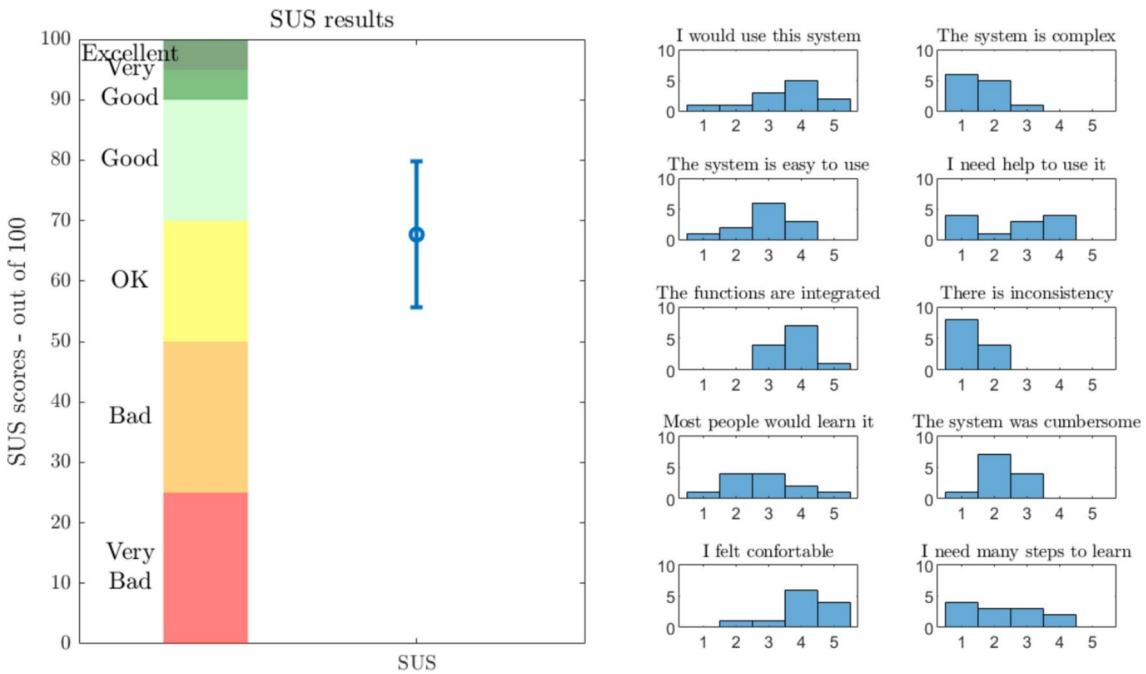

Fig. 7 (LEFT) Usability score distribution, with mean and standard deviation, compared to the SUS scale. (RIGHT) Distributions of the scores for the individual SUS questions

significantly correlated, with a correlation coefficient of 0.63 ($p_{value} < 0.05$).

5 Discussion and conclusions

From the results of the GLM model, we observe a statistically significant impact on the error when using our application compared to not using it, and such a difference is not influenced by the the different exercises. Our feedback system consistently reduces trajectory-execution kinematic errors, as demonstrated in Table 3, compared to tests conducted without HoloLens. The improvement obtained in the End-effector space is then confirmed in Joint space. The statistical analysis of the results indicates that participants get the greatest improvement when executing T4, thanks to the feedback system. This could be attributed to the fact that the fourth trajectory is more complex and therefore less intuitive to execute. This assumption is generally confirmed if we consider that T2 and T3, which are more linear than the other two trajectories, result in slightly smaller error reductions. In Fig. 9 we can appreciate the global trend of the errors along with the different feedback modalities, both in End-effector and Joint space.

If no big difference is observed between the errors obtained with the three CIs in the end-effector space, C3 yields the best results in the joint space. We could observe that, during the execution of the tasks with the feedback system showing the smallest confidence interval, the users moved slowly (time for cycle execution in C3 is $t_{C3} = 6.07 \pm 0.85s$ against $t_{C1} = 4.69 \pm 0.71s$ and $t_{C2} = 4.99 \pm 0.77s$), trying to carefully track the trajectory, which was perceived as more difficult to travel than in the other conditions. This behaviour favoured a correct positioning of all the user's joints, reducing the kinematic error also at the shoulder and elbow levels. The participants obtained significantly better performance with the use of our application. All the results come from tests conducted with healthy subjects, possessing normal abilities in executing physiological motor tasks and who therefore could be considered as not really in need of feedback support. We could consequently expect our system to produce a greater improvement with motor-impaired subjects with adequate cognitive functions. With them, we can also expect greater differences in the end-effector tracking performance between the three CIs.

Concerning the qualitative results coming from the healthy participants' questionnaires, we can say that the scores obtained are encouraging. The *Comfort of the device* was ranked 4.04 out of 5, confirming the idea that AR headsets are an appreciated solution (Jordan and King 2011). The guiding interface was highly positively evaluated (4.57/5) for its efficacy. Having an effective user interface

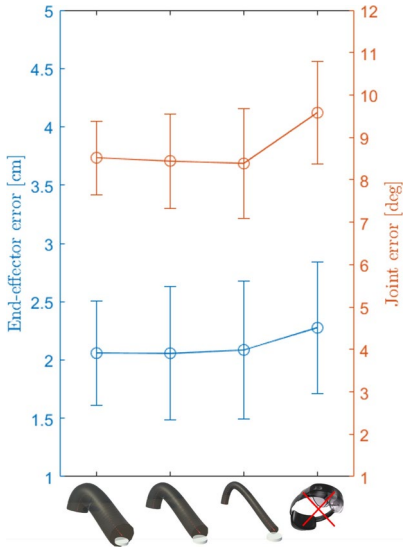

Fig. 9 Error statistics in End-effector (left-axis) and Joint (right-axis) space. The results depicted in this summary are evaluated considering all the trajectories and show the median errors collected in C1, C2, C3 and NoHolo modalities (from left to right)

is fundamental to ensure that the system is manageable also by subjects suffering from neurological diseases and, therefore, not necessarily practical when dealing with advanced technologies. One of the participants was colourblind and confirmed that, thanks to the presence of symbols on the buttons and the different sizes of the spheres composing the trajectories, the guiding interface was intuitive. The category that obtained the lowest score is *Reliability and stability of the hand-tracking system*: unluckily, the HoloLens hand-tracking algorithm suffers from some limitations when the hand is either too far or too close to the visor. Guaranteeing the execution of therapy exercises in an environment with constant lighting conditions and minimising reflections from mirrors, glass, or shiny surfaces would help improve the stability of the Hololens tracking performance. This would guarantee a better experience with our application and especially when dealing with patients, would reduce the cognitive load required to use the system. Overall, the positive feedback from healthy participants encourages potential future testing with patients.

The feedback coming from the clinical personnel confirmed the positive conclusions. The SUS score (68/100) ranked our system as "OK". Even if this value is slightly lower than the boundary for classification as "GOOD", we need to consider it in light of the SUS scores attributed by participants of other studies to applications developed with HoloLens. In Escalada-Hernández et al. (2024), some medical students rated a surgical training application in AR with a mean SUS score of 73.15. Hsieh et al. (2020) developed an application for fall-risk assessments with older adults, and the participants of their study gave the system an average

score of 71.9. Considering the standard SUS questions presented in Moosburner et al. (2019), the Usability score gained by a surgical HoloLens-based application was 70. Our framework seems to be therefore in line with the average score of similar applications. It's important to note that these applications have different medical objectives and, so far, no other system has been developed for the same purpose as our framework. Moreover, given the limited time the therapists had for training with our system and its present condition as a prototype, we believe there are high chances of improvement in terms of usability. In future versions of our application, we will work on refining the user interface and on a detailed user manual, with easy explicative videos, to facilitate the learning process, especially for subjects with limited confidence in technology. We will also organize dedicated training sessions for clinicians to better support their process of familiarization with our system.

The results of the TAM are encouraging. The clinicians' Willingness To Use the system and the Perceived Usefulness both scored over 4 out of 5 points. PEOU scored 3.5 out of 5, which aligns with the responses from the SUS questionnaire. In fact, as we can notice from Fig. 7, the questions that lowered the final score are those related to the easiness and readiness of use ((3): *The system is easy to use*, (4): *I would need help to learn how to use the system*, (7): *Most people would learn how to use the system easily*). Even though the system may not be seen as completely easy or intuitive to use, this does not significantly impact the intention to use it for rehabilitation sessions (PEOU-WTU correlation coefficient = 0.42). The low correlation between PEOU and WTU aligns with our hypothesis that the perceived complexity of the system can be addressed with additional training and is not currently viewed as a barrier to using the application. The multiple regression model confirms the prevalence of the effect of PU on WTU. Both *Importance of Tridimensionality* and *Importance of Graphical aspects* obtained a final score of over 4 out of 5 points, confirming that graphics and details refinement are considered relevant to enhance users' engagement and compliance with the therapy. Both from the correlation analysis and the regression model we can see how Tridimensionality is considered as slightly more relevant for the utility of the system than the Graphical aspects.

We can notice how the Attitude Towards Technology of the participants has a positive and significant correlation with the scores of the *WTU*: therapists who are more confident with technologies tend to learn faster how to use the headset and are more interested in using it. Given also that it is demonstrated that good levels of digital literacy can enhance the benefits of the application of rehabilitation technologies (Stark et al. 2023), we can hypothesize that, in a future study on patients, participants with a good attitude towards technologies will experience greater improvements with our system.

No disturbances related to motion sickness were reported, suggesting that AR headsets could also be a promising solution to be tested with patients. Even if it is generally recognised that AR motion sickness effects are reduced if compared to those of VR (Lawson and Stanney 2021), an important future step for this work would be testing the application with patients suffering from different kinds of neurological disorders, to verify if the results we gathered with healthy subjects are confirmed and prevent any unwanted cybersickness effect. A feasibility test involving patients to investigate AR effects would also help us define which categories of patients can better tolerate technology, ultimately benefiting them more in terms of rehabilitation effects.

During our test, we interviewed the therapists regarding the types of patients who could benefit from using our system. They all recommended it for neurological patients who can engage with the therapist behaviourally and possess cognitive and attention levels that enable them to comprehend the required tasks. They should have already regained the motor abilities needed to execute functional gestures and just have to improve the accuracy of their movements. Further exploring alternatives and additions to our applications, involving other feedback modalities (such as auditory complementary indications), could help broaden the target of patients that can benefit from our device.

We can then conclude, based on both the kinematic analysis and the therapists' evaluations, that the system we developed provides precise three-dimensional feedback on the execution of therapeutic exercises and has the potential to effectively support patients and therapists. The kinematic improvements obtained by our healthy participants while using the HoloLens feedback demonstrate its feasibility in enhancing tracking accuracy and, therefore, in potentially supporting rehabilitation outcomes in the long term for subjects with neurological disorders. The framework was appreciated both by healthy participants and clinicians. The obtained SUS score indicates that the system's usability is in line with other prototypes in the field of AR for healthcare and that, especially considering the high levels of perceived utility and intention to use it expressed by therapists, there is space for improvement and further exploration with patients.

Appendix A Questionnaire for the healthy participants

Clarity of the calibration

- The process explanation is clear and understandable;
- The use of the index to locate the marker is not intuitive;
- The index tracking is stable;
- The button to fixate the marker is difficult to use.

Usability of the trajectory manipulation mechanism

- The position of the trajectories is clearly identifiable and easy to reach;
- The desired trajectory is easy to select;
- The positioning mechanism is disorienting;
- The selection of the CIs is easy;
- The hand tracking to position the hand is stable.

Effectiveness of the guiding interface

- It is easy to understand where the trajectory is and how to travel it;
- The colour code and the spheres help in understanding how to navigate the trajectory;
- The real trajectory is clearly visible;
- Colours and shadows help perceive the tridimensionality and depth of the objects.

Reliability and stability of the hand-tracking system

- The recognition of the segments of the hand is always correct;
- I never lost track of the hand and had to change my position to have the system recognise it again;
- It is easy to interact with the buttons.

Comfort of the device

- The headset is easy to use;
- I did not have difficulties in moving due to the headset encumbrance;
- Holograms colours were easy to recognise;
- The weight of the device is not too high to bother me;
- I had difficulties in seeing the holograms;
- I experienced nausea at least once during the use of the headset.

Appendix B TAM questionnaire for the clinical staff

Willingness to use

- I think I would like to use this system for my patients;
- I believe I would likely use the system during my therapy sessions as a feedback system for my patients;
- I think I do not want to include the system in my therapy sessions;
- I do not think I am interested in using the headset.

Perceived ease of use

- I find the system difficult to use;
- I believe it is easy for the patient to learn how to use the system;
- I believe it is easy for me to learn how to use the system;
- Interacting with the system is often frustrating;
- I find it easy to manage the system.

Perceived usefulness

- I think the system is a valid instrument to support rehabilitation;
- I believe the system can help patients in the execution of exercises;
- I do not think that the feedback system is useful for the patient or helps them accurately exercise;
- I believe the system does not support any aspect of my rehabilitation work.

Tridimensionality

- I think the 3D feedback system is a useful addition with respect to other feedback systems;
- I do not think that tridimensional feedback improves the positive effects of therapy if compared to other simpler systems (just target points, vocal instructions...)

Independence of the therapy

- I think that the autonomous reproduction of movements I taught has beneficial effects on the therapy;
- I think the system allows the patients to execute specific movements I want them to do, without my guidance.

Graphics

- I think the patient benefits from the color-coded feedback;
- I appreciate the colour scale for its immediateness;
- I believe that the different dimensions of the trajectories are useful to improve the efficacy of the system;
- I do not think the colour scale helps me understand how well the patient is performing the task.

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Author contributions BL and MG conceived the idea and carried out the experiments, BL developed the application, analyzed the data and wrote the manuscript, MG verified the analytical methods, PT and AS organised the experimental sessions with the clinicians and contributed to the final version of the manuscript, FB and AP supervised the work and contributed to the final version of the paper.

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Not applicable.

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

Declarations

Conflict of interest FB, AP and MG hold shares in AGADE srl, Milan, Italy. The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential Conflict of interest.

Ethics approval and Consent to participate All the participants in the experiments signed an informed declaration of consent and the tests were approved by the Ethical Committee of Politecnico di Milano (approval n. 8/2022 - 16/02/2022).

Consent for publication The questionnaires were developed in compliance with the Italian personal data protection law and the data were used exclusively for the purposes of study and scientific research and processed pursuant to Art. 13 of EU Regulation 2016/679 (General Data Protection Regulation). By responding to the questionnaire, the participants were informed and accepted that their answers were recorded and analyzed in aggregate form.

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