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Assessing Upper Extremity Motor Dysfunction Using an Augmented Reality Game

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ABSTRACT

Advances in technology offer new opportunities for a better understanding of how different disorders affect motor function. In this paper, we explore the potential of an augmented reality (AR) game implemented using free hand and body tracking to develop a uniform, cost-effective and objective methods for evaluation of upper extremity motor dysfunction in different patient groups. We conducted a study with 20 patients (10 Parkinson's Disease patients and 10 stroke patients) who performed hand/arm movement tasks in four different conditions in AR and one condition in real world. Despite usability issues mainly due to non-robust hand tracking, the patients were moderately engaged while playing the AR game. Our findings show that moving virtual objects was less targeted, took more time and was associated with larger trunk displacement and a lower variability of elbow angle and upper arm angle than moving real objects. No significant correlations were observed between characteristics of movements in AR and movements in the real world. Still, our findings suggest that the AR game may be suitable for assessing the hand and arm function of mildly affected patients if usability can be further improved.

Keywords: Augmented Reality Games, Engagement, Upper Extremity Motor Dysfunction, Assessment, Parkinson's Disease, Stroke patients.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities; H.5.2 [Information Interfaces and Presentation]: User Interfaces—Interaction Styles; J.3 [Life and Medical Sciences]: Medical information systems.

1 INTRODUCTION

More and more people are affected by disorders that impair their motor function, e.g. neurovascular diseases, neurodegenerative diseases, and musculoskeletal pain conditions. As the majority of these people are elderly, it becomes a necessity to develop cost-effective evaluation methods for diagnosis, treatment and monitoring of patients with motor dysfunctions.

Currently, each medical discipline uses disease-specific clinical tests to assess motor (dys)functions, based on subjectively scored and low-resolution rating scales, qualitative video analysis, or cumbersome marker-based motion capturing. Rapid technological developments have resulted in a number of attempts to objectively quantify motor symptoms in laboratory settings or to develop wearable technology for free-living monitoring of for example Parkinson's Disease (PD) [11], [13], [32]. Unfortunately, variations in tasks and environment are often not considered, despite being essential aspects of daily life. Current methods often consist of simple, repetitive tasks that may lead to loss of interest of the patients. Moreover, adaptation of the tasks according to the actual physical and intellectual capabilities of each patient is difficult.

In this context, the clinical community needs improved assessment methods to provide objective and quantitative measurements of human motor function in a controlled and challenging environment that offers the possibility to perform a variety of movements. In addition to being relevant from the clinical perspective, these methods should also be patient-tailored and patient-friendly, i.e., adaptive, easy to use and engaging for the patient.

Mixed reality (MR) environments present within a single display real world and virtual world objects together [30]. MR interactive systems have a high potential in becoming a viable solution for the assessment of motor function in a simulated environment. Virtual reality (VR) totally immerses a user in a completely synthetic world [30]. VR has already proven to offer great opportunities for rehabilitation of several patient groups [3], as it enables real-world situations to be simulated, thereby giving the therapist full control over parameters (e.g. sizes, distances, velocities, trajectories etc.) related to a specific movement of interest. The total visual isolation from the real world, however, may interfere with natural behaviour of patients. This issue can be circumvented by using AR, which allows the user to see the real world, with virtual objects superimposed upon or composited with the real world [2]. AR thus supplements reality and provides patients with a more realistic experience that results in more intuitive natural interaction [19].

There are multiple modalities for interaction between the hand or body and the virtual content, using input from different types of systems and sensors. Some are attached to the hand or body, like various types of markers (e.g. fiducial, infrared or magnetic markers detected by special cameras), or gloves [37], [40] or full-body suits [38] that provide relative positions of the fingers or full-body 3D coordinates. Exoskeleton haptic devices have been developed to apply force to the user's fingertips (e.g., Rutgers II-ND Hand Master glove, CyberGrasp and CyberForce [40]). Recently, systems for contact-less tracking of the hands [39], [41] and body [35] have been developed, which are based on depth cameras with structured light.

Interactive AR systems have already been successfully developed for rehabilitation of motor function of the arm and hand. Several AR systems have used a variety of interaction methods such as gloves [26], [33], real objects [1], [23], [25], small markers attached to the hand [19] and contact-less tracking [10], [31]. Thereby, different visualization styles have been used, such as monitors [10], [25], [31], [33], 2D or 3D rendering in direct environment of the patient (2D: [19], [23], 3D: [1], [26]).

Most AR systems for rehabilitation involve exercises implemented as games in virtual worlds. These have proven to be an excellent tool to motivate [34] and engage patients to perform repetitive tasks [5] during rehabilitation. These games may be designed to create situations of flow (i.e. "the state in which people are so involved in an activity that nothing else seems to matter" [9]) that could motivate the patient to perform various movements to their full potential. Moreover, the simulated environment offers high flexibility with regard to the shapes, positions and trajectories

of objects, allowing for adaptation to the capabilities of each patient. Adaptable exercises in which patient's performance is used to set the targets, are known to increase patient motivation [22].

Creating engaging tasks inside virtual environments has already shown its potential for rehabilitation of motor function, especially by motivating patients to perform repetitive exercises meant to improve their hand and arm mobility. In contrast, research to date has not focused on the use of virtual environments for objective assessment of the type and severity of arm and hand dysfunction. Compared to systems focusing on rehabilitation, a requirement for such systems is to generate quantitative, accurate data that are relevant for monitoring disease progression over time, and to evaluate the response to therapeutic interventions. To our knowledge, only Khademi et al. [24] combined free-hand interaction with games to develop a system for rehabilitation of stroke patients in which they reported strong correlations between game scores and standard clinical assessment scores (e.g. Fugl-Meyer [15] and Box-and-Blocks tests [8], [28]). Although promising, it has been advocated that correlation with a clinical score is not sufficient to provide evidence for diagnostic validity [32]. Furthermore, it should be noted that patients were not immersed in a 3D environment in this study [24], but that the game was visualized on a laptop. This is unfortunate, because movement behaviors might have been impacted by the need to translate 2D perception into 3D movements.

We report on the design of an AR game and its implementation using contact-less tracking of the hand and body to facilitate unobtrusive and patient-friendly methods for objective assessment of upper extremity motor dysfunction. In this context, it is essential that patients are able to naturally interact with the virtual environment and to perceive the correct 3D position of objects around them. For this purpose, we use an Optical See-Through (OST) head-mounted device (HMD) for stereo visualization of virtual content, allowing for an accurate depth perception of virtual objects. While playing the game in AR, the patient's movements are recorded to allow for objective, quantitative evaluation of their motor function.

Following earlier experiments with healthy users [12], [29], we conducted a study with 20 patients (10 PD patients and 10 stroke patients) who performed hand/arm movement tasks in four different conditions in AR and one condition in real world. We describe a user experiment, in which we investigated how virtual hand visual feedback, puzzle types and interaction modalities affected the movement of the patients, task load perception, game experience and usability of the AR system. In addition, we explored to what extent movements in AR resemble real world movements. Reach-to-grasp movements toward a target of real and virtual objects in a different AR set-up had also been explored by Mason et. al. [27].

2 User Study Design

This section describes an experiment with two goals: first, to collect feedback from patients on using our AR system for assessing their hand/arm motor function, in order to evaluate usability, game experience and task load of the current AR game and to get input for further developments of the system; and second, to compare characteristics of movements performed in AR (i.e., while interacting with virtual objects) with those of movements performed in the real world (i.e., while interacting with real objects) to examine whether movements in AR provide an indication of motor (dys)function in the real world, and whether movements in AR are relevant for assessing a patient's medical condition.

2.1 Task Design

Based on the consultation of 1 clinician, 1 movement scientist and 7 PD patients, we designed the game "post office trouble" [7] which focuses on a simple but functional task, i.e., reaching and grasping an object. The game puts a player in the position of a post office worker who has to sort packages, thereby making as few mistakes as possible. The player sees different target boxes, each corresponding to a destination which is stated on top of the box. The package that needs to be sorted appears in front of the participant. Each package shows an image providing a hint on the destination.

The resulting AR scene consists of four target boxes (see Fig. 1 left), each positioned in one corner of a A0 sized tracking marker (see Fig. 2) such that one target is presented in each quadrant of upper extremity workspace (i.e., ipsilateral or contralateral to the tested arm, and above or below shoulder level).

Patients are wearing an OST-HMD (see Fig. 2 and Fig. 3) and are sitting in a chair about 1.2 m in front of the tracking marker. A patient's task is to grasp the package that appears in the centre of the marker (using the thumb and index finger) and move it towards its correct destination box. The "correct" destination box is determined by the image displayed on the side of the package that initially faced the user. For example, when this image is just a plain colour, the package has to be put in the destination box with the same colour (e.g., in Fig. 1 left the package has to be placed into the upper right box).

When a patient interacts with the package, visual feedback is provided as a cyan halo displayed around the package. During interaction, the package follows the position of the hand and the orientation of the palm (i.e., the blue component of the virtual hand in Fig. 1 left).

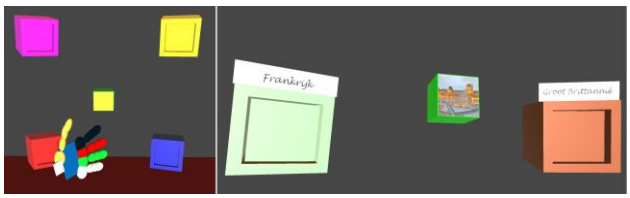

Fig. 1. (left) A screen capture in Unity3D with the AR scene for the color based puzzle with virtual hand (C1); (right) the upper half of the AR scene for the "touristic attractions" based puzzle (C3). The dark grey background becomes almost transparent when displayed in the OST-HMD and it is practically invisible to the user.

We introduced four different conditions (see Table 1) to examine how virtual hand visual feedback, puzzle types and interaction modalities affect the movement of the patients, task load perception, game experience and usability of the AR system. Condition C1 is considered the baseline condition for all comparisons. The other three conditions C2-C4 each differ from C1 by only one feature (Table 1; printed in bold).

Table 1. Overview of conditions

Condition	Virtual Hand	Puzzle type	Interaction modality
C1	Yes	Color	Grasping
C2	**No**	Color	Grasping
C3	Yes	**Image**	Grasping
C4	Yes	Color	**Pointing**

With regard to virtual hand visual feedback, we investigated the effect of the absence of a virtual representation of the hand (C2). In a "perfect" AR system, providing a virtual representation of the hand would no longer be necessary, because hand tracking and stereo calibration of the HMD would allow for a precise alignment of the virtual hand with the real hand. Given the current status of

technology, however, we expected that a visualisation of the virtual hand would aid participants in completing the task.

With regard to puzzle type, we expected that a themed puzzle would be more cognitively 'challenging' and more engaging than simple colour sorting. To explore the possible impact of a cognitive load on the hand/arm motor (dys)function, we introduced a themed puzzle (C3; Fig. 1 right), where the image on the package depicts a touristic attraction. The package then has to be put into the destination box of the corresponding country.

With regard to interaction modality, we evaluated whether user experience and movement characteristics are affected by an easier interaction modality (i.e. "pointing" with the index finger (C4) instead of "grasping" with the thumb and index finger).

2.2 Participants

Ten PD patients (7 male; age 49 to 80 years old; M=64.2; STD=8.2) and ten stroke patients (10 male; age 54 to 83 years old; M=68; STD=9.7) participated in this study. Informed consent was obtained according to the Declaration of Helsinki. All procedures performed in this study were approved by the ethical committee of the Leiden University Medical Center. All participants received a gift card to the value of € 20 as a reward for their participation.

In PD patients, disease severity ranged from Hoehn-Yahr stage 1 (unilateral symptoms) to 4 (severely disabled) [18] (median = 2.5), with disease duration ranging from 3 to 23 years (M=11.4; STD=6.7).

All stroke patients had some residual upper extremity motor dysfunction, but were able to voluntarily move their affected arm, scoring 1 to 3 on the item "block 5 cm" of the Action Research Arm Test (ARAT [6]). Time since infarct (n=8) or haemorrhage (n=2) ranged from 1 to 8 years (M=3.4; STD=2.1). None of the participants had used a HMD before and they had no experience with a natural user interface (NUI).

Participants were asked to perform the tasks with their most affected hand. For PD patients, this was the hand with the highest score on the items of the MDS-UPDRS part III concerning the upper extremity [16]. If it was not possible to test the most affected hand due to technical issues (i.e., problems with hand recognition; 1 PD and 3 stroke patients) or physical limitations (i.e., unable to raise the hand in view of the camera; 1 stroke patient), the unaffected or less affected side was tested.

Being severely disabled by the disease (both mentally and physically, Hoehn-Yahr stage 4), one PD patient was not able to perform any of the required tasks in AR and another PD patient only performed C4 with the less affected hand. One stroke patient performed under three conditions (C1, C3 and C4) because of fatigue/boredom. Therefore, the results presented in section 3 are based on 8 PD and 10 stroke patients (except for comparisons involving C2, which are based on 8 PD patients and 9 stroke patients, and comparisons involving real world movements, which are based on 7 PD patients and 7 stroke patients due to technical issues).

Fig. 2. Stroke patient during the experiment.

2.3 Measurement instruments and data collection

2.3.1 Hardware

For the stereoscopic visualization of the graphical content, we use the AIRO II HMD from Cinoptics (specifications: FOV ~ 40° diagonal, display technology OLED, aspect ratio 16:9, display resolution 1280×720), with the Intel® Realsense F200 mounted on top of it (see Fig. 3). The application runs on a Dell Precision M4800 laptop.

In order to record the movement of the arm, we connected to the same laptop a Kinect™ v2 for Windows, placed at a distance of 3 meters with approximately 45° angle relative to the left side of the patient (see Fig. 2) which appeared the optimal positioning to avoid interference with the Intel® RealSense F200.

Fig. 3. Cinoptics AIRO II HMD for AR with the Intel® RealSense F200 mounted on top of it.

2.3.2 Software

We used Unity3D as a platform to integrate all the software components for the experiment.

For spatial and temporal alignment of the real world and the virtual world, we used the Vuforia tracking library [36].

The trigger zones that detected when a package reached its destination, were approximately 7 x 7 x 7 cm inside the destination boxes. The packages (5 x 5 x 5 cm) were generated 15-20 cm in front of the destination boxes, and at a distance of 90-100 cm from the marker.

Hand movements in AR conditions were tracked using the Unity3D plugin of the Intel® RealSense SDK (version 7.0.23.8048) and the Intel® RealSense Depth Camera Manager F200 (version 1.4.27.41944) [39], which applies a hand-tracking algorithm to depth information obtained by the camera to estimate the 3D positions of 21 'joints' of the hand, such as the wrist, the finger joints and the finger tips (approximately 30 frames/second).

Arm movements in AR conditions and in the real world were tracked using the .NET API provided by the Kinect for Windows SDK 2.0 (version 2.0.1410.19000) [35]. In specific, the Kinect for Windows SDK 2.0 provided, with a sampling rate of 30 frames per second, the 3D positions of 13 estimated body points, i.e., the head, neck, spine shoulder, spine mid, spine base and left and right shoulder, elbow, wrist and hand.

2.3.3 Questionnaires

In order to obtain feedback from patients on the AR system, different questionnaires were used to assess task load, usability and engagement.

The NASA-TLX questionnaire [17] was used to assess the perceived task load.

The System Usability Scale (SUS) [4] measured the usability of our AR system.

Engagement of the participants was evaluated using the Game Experience Questionnaire (GEQ) [20]. The core module of GEQ evaluates seven different dimensions of experience that are associated with "being engaged": competence, sensory and imaginative immersion, flow, challenge, positive affect and negative affect, tension and annoyance. For a positive score, the first five dimensions should have a high ranking and the latter two

should have a low ranking. For our user study, we used the In-game version of the GEQ, which is a concise version of the core questionnaire and is developed for assessing game experience at multiple intervals during a game session [21] (see Table 2).

Responses for NASA-TLX questionnaire were given on a seven point Likert scale from 1 (Not Very) to 7 (Very). All the other questions were answered on a five point Likert scale from 1 (Not Very) to 5 (Very).

Table 2. In-game version of the GEQ

No.	Question	Dimension [a]
1	I was interested in the game's story	I
2	I felt successful	CO
3	I felt bored	NA
4	I found it impressive	I
5	I forgot everything around me	F
6	I felt frustrated	TA
7	I found it tiresome	NA
8	I felt irritable	TA
9	I felt skilful	CO
10	I was fully occupied with the game	F
11	I felt content	PA
12	I felt challenged	CH
13	I had to put a lot of effort into it	CH
14	I felt good	PA

[a] Competence (CO), sensory and imaginative Immersion (I), Flow (F), Challenge (CH), Positive Affect (PA), Negative Affect (NA), and Tension and Annoyance (TA).

2.3.4 Data collection procedure

Throughout the experiment, participants sat in a chair with their feet supported.

First, participants performed reach-and-grasp movements in the real world. To this end, an ARAT kit [6] was placed on a tabletop in front of the participant (see Fig. 4), such that back of a shelf (37 cm above the tabletop) could be reached when the arm was held outstretched.

Participants had to move a 5x5x5 cm wooden cube from the starting position (i.e., on the tabletop, in front of the shoulder) to a marked target position on the shelf, either 20 cm to the left or 20 cm to the right of the starting position. The movement was performed twice towards each target position, with both the left and the right hand (order counterbalanced over participants) and it was recorded using the Kinect™.

Fig. 4. The ARAT kit used for reach and grasp movements in real world.

In the main phase of the experiment, participants started with a training session to get used to the OST-HMD and to the hand tracking system for the free hand interaction within the virtual environment (two packages per condition; no data recorded). Afterwards patients played the game (i.e. put 12 packages into the correct destination boxes) under each of the four conditions C1-C4, while their hand and body movements were recorded. The order for the correct destination boxes was predefined, with the rule that in each round (three rounds in total) the patients had to move the package towards every corner of the marker.

The order of conditions was randomized so that comparisons between conditions would not be biased by a systematic learning effect.

After each condition, 25 questions (i.e., NASA-TLX, subset of GEQ (Table 2) and subset of SUS (questions 3, 6, 7, 8, and 9 in [4]) were asked to the patient. The other questions from the SUS questionnaire were asked only once at the end of the experiment, as they refer to the general system usability.

The total duration of the experiment varied from patient to patient, from 40 minutes up to 2 hours. The big variance of the completion time may be explained by the wide range of patients' ages, by the different degrees of disease severity and by the disease duration.

2.4 Data analysis

Aggregated scores were computed for each questionnaire. For the NASA-TLX, the overall score was the mean value of Q1-Q5 and the inverted score of Q6 (see [17]). For the GEQ, a score was computed for each dimension as the mean value of the two questions from that dimension (see Table 2). The overall GEQ score was calculated as the mean value of all dimension scores (after inverting the scores on negative dimensions). For SUS, the scores were computed as described in [4].

In order to measure task performance and execution in AR, the following variables were extracted from log files: *timeInteraction*, i.e., time when the participants interacted with the green package; *timeNoInteraction*, i.e., time when there was no interaction; and *timeHandLost*, i.e., time when the hand was not detected by the depth sensor. For each condition, "measured" performance was defined by the number of packages moved into the correct destination box.

To evaluate movement characteristics, the 3D positional data of 'body points' and 'hand joints' were first resampled to a uniformly distributed discrete time series (30Hz) using linear interpolation. Thereafter, the data were low-pass filtered (3rd order Butter worth, cut-off frequency = 5Hz) to reduce measurement noise.

For AR, analyses were performed on the samples in which the hand was interacting with the object. Hence, 'breaks' and movements made in an attempt to establish hand recognition or interaction were not analysed, but are reflected in total duration (see below) and the previously described variables *timeNoInteraction* and *timeHandLost.*

For movements in the real world, the data segment containing the movement of interest (i.e., moving the block from start position to target position) was identified using a running window analysis on velocity of the wrist in the vertical direction. The so obtained segments were visually inspected and their start and/or end time points were manually corrected if necessary.

To quantify the reaching movement in AR and the real world, we calculated several outcome measures. Total duration was defined in AR as the time from first interaction with the package until it was placed in a destination box, and in the real world as the length of the selected segment.

The elbow angle was defined as the angle (in °) between the upper arm and the lower arm, and the upper arm angle as the angle of the upper arm relative to the horizontal plane, with positive values indicating that the upper arm was below shoulder level.

The maximum absolute angular velocity of the elbow and upper arm (both in °/s) as well as the maximum absolute velocity of the wrist and trunk (in m/s; based on the 'spine mid' coordinate provided by Kinect™) were calculated as outcome measures. In addition, variability (SD) of the elbow and upper arm angle (in °) was calculated, with smaller values indicating that the arm was held in a more constant position during the movement.

The total length of the trajectory transversed by the wrist (i.e., the numerical integral of the absolute velocity; in m) reflected the "directness" of the movement from start to target position. The linear distance between the trunk position at the start and the end of the movement (in m) provided an indication of involvement of the trunk.

Additionally for the AR conditions, the grasping movements of the hand were quantified by means of the mean and SD of the linear distance between the tip of the thumb and the index finger (TIF_{mean} and TIF_{SD}).

2.5 Statistical analysis

For each of the two groups of patients (i.e., PD and stroke) pairwise comparisons between the baseline AR condition and each of the other three AR conditions were performed, focusing on the overall task load (NASA-TLX), usability (SUS), task performance and various movement characteristics.

To examine whether the presence or absence of the virtual hand affected specific components of task load, individual questions from NASA-TLX were compared between C1 and C2. To explore whether an image-based puzzle increased the challenge and engagement of the game, mental load (NASA-TLX question Q1) and GEQ were compared between C1 and C3.

Kolmogorov-Smirnov tests (α=.05) were used to assess whether the data were normally distributed within each group, for each condition [14].

The data from questionnaires, game statistics and log files in each group were not normally distributed. Therefore, all values are presented as median [interquartile range] and all pairwise comparisons between conditions were performed using the nonparametric Wilcoxon Signed-Rank test (α=.05).

For the pairwise comparison of movement characteristics between AR conditions, for each outcome parameter the median of all trials per condition was used, to reduce the influence of outliers. After ^{10}log transformation of total duration, maximum trunk velocity and trunk displacement, data were normally distributed in circa 90% of all conditions. Although transformed data were used for statistical analysis of these parameters, for reasons of clarity the untransformed data are presented in the Results. Outcome parameters were each submitted to a mixed ANOVA with group (PD vs. stroke) as between-subjects factor and condition (i.e., C1 vs. C2, C1 vs. C3, or C1 vs. C4) as within-subjects factor.

For comparing movement characteristics between AR (C1) and the real world, only data corresponding to movements towards the upper targets of AR were used. For each outcome measure, the median over trials per target position (ipsilateral or contralateral to the tested hand) was calculated. After ^{10}log transformation of total time, data were normally distributed in circa 90% of all conditions. Outcome parameters were each submitted to a mixed ANOVA with group (PD vs. stroke) as between-subjects factor and condition (i.e., AR C1 vs. reality) and target position (ipsilateral vs. contralateral) as within-subjects factor.

For all ANOVAs (α=.05), effect sizes were quantified as partial eta squared (η_p^2) and post-hoc analyses of significant interaction effects were performed using two-tailed *t*-tests. Values of movement characteristics are reported as mean ± standard deviation.

Spearman's rho (ρ, with α=.05) was used to investigate *1)* if SUS scores were monotonically related with GEQ, measured performance and perceived performance (i.e., NASA-TLX question Q3) in each AR condition; *2)* if movement characteristics in AR C1 were related to usability (SUS score) or perceived workload (NASA-TLX overall score); and *3)* if characteristics of movements in AR C1 were related to characteristics of movements in the real world. For the latter purpose, data of the two patient groups were combined.

3 Results

For all AR conditions, usability scores of individual patients and significant correlations between usability and GEQ, perceived performance and measured performance for both patient groups are presented in section 3.1.

The outcomes of pairwise comparisons between AR conditions are presented in the subsequent sections (3.2 to 3.4). Significant effects obtained from the mixed ANOVAs for each of the movement characteristics are presented in Table 5.

Results of the analyses involving a comparison between conditions are described in the text and presented in Fig. 5. Results of the comparison between movements in AR and the real world are presented in Table 5 and Fig. 6, and are described in section 3.5.

3.1 Usability scores and correlations with GEQ, measured and perceived performance

Table 3 presents the values of the SUS in all AR conditions, for PD and stroke patients. A system is considered to have good usability if SUS scores are above 68 [4].

Table 3. SUS scores for individual patients

PD patients			
C1	**C2**	**C3**	**C4**
35.00	35.5	50.00	42.50
72.50	60.00	60.00	67.50
60.00	57.50	47.50	65.00
20.00	17.50	22.50	20.00
62.50	52.50	55.00	62.50
82.50	**65.00**	**75.00**	**77.50**
37.50	35.00	55.00	57.50
62.50	52.50	65.00	70.00

Stroke patients			
C1	**C2**	**C3**	**C4**
57.50	52.50	55.00	67.50
80.00	77.50	65.00	62.50
80.00	77.50	80.00	77.50
100.00	**100.00**	**100.00**	**100.00**
55.00	55.00	47.50	62.50
70.00	72.50	77.50	80.00
65.00	50.00	62.50	57.50
40.00	47.50	45.00	50.00
50.00	-	42.50	50.00
27.50	22.50	32.50	40.00

The correlation coefficients between SUS and GEQ, measured performance and perceived performance are shown in Table 4. Higher usability was associated with more engagement (PD: C3, stroke: C1, C2) and, in stroke patients, with better perceived and measured performance (significant in C2 only).

Table 4. Correlations between SUS and GEQ, perceived performance and measured performance

	C1	C2	C3	C4
(SUS, GEQ)				
PD	.64	.52	.84 *	.17
stroke	.66 **	.79 **	.50	.52
(SUS, perceived performance)				
PD	.17	.34	.17	.11
stroke	.62	.93 **	.40	.60
(SUS, measured performance)				
PD	.51	.20	.24	NaN[a]
stroke	.72	.81 **	.79	.45

Significant correlations are indicated by asterisks (* p <.05, ** p<.01);
[a] the measured performance had constant values in this condition

3.2 C1 vs. C2: virtual hand visual feedback

To determine the effect of the presence or absence of a virtual hand, we compared the task load, usability scores and task performance and execution between C1 and C2.

The NASA-TLX overall score of PD patients showed that C1 was less difficult than C2 (2.8 [2.7-3.7] vs. 3.9 [3.7-4.4]; Z=-2.53, p=.01); while for stroke patients there was no statistical difference between overall scores. Irrespective of condition (i.e., both in C1 and C2), responses for NASA-TLX questions related to mental and physical demands (Q1, Q2) and effort (Q4) had median values above 3.5, whereas responses for questions concerning "rapid pace" and stress (Q3 and Q5) had median values under 2.5, for both PD and stroke patients.

The SUS scores indicated that for the PD patients condition C1 had a higher usability than C2 (61.25 [36.25-67.5] vs. 52.5 [33.75-58.75]; Z=2.55, p=.01). For stroke patients, SUS scores were not significantly different between conditions.

For the PD patients, providing visual feedback for the hand helped them to have better hand recognition (i.e., *timeHandLost* was lower in C1 compared to C2 (48 [20-141] vs. 131 [76-272]; Z=-1.96, p=.049)) and better interaction with the virtual objects (i.e., *timeNoInteraction* was lower in C1 than in C2 (134 [71-370] sec vs. 500 [300-874]; Z=-2.38, p=.02)).

For stroke patients, visual feedback also led to a better hand recognition (i.e., *timeHandLost* was lower in C1 than in C2 (39 [25-60] vs. 60 [28-95] sec; Z=-2.09, p=.04)), while *timeNoInteraction* was not significantly different between conditions. The presence or absence of a virtual hand did not affect *timeInteraction* in any patient group.

With regard to the movement characteristics, significant interaction effects between condition and group were observed for variability of elbow angle and the maximum angular velocity of the upper arm, whereas these interaction effects just failed to reach significance for variability of the upper arm angle and maximum angular velocity of the elbow (p=.05 and p=.06, respectively). Post-hoc analyses for each of these variables point in the same direction, with a decrease for stroke patients from C1 to C2 and for PD patients a (non-significant) increase from C1 to C2. As a result, values of stroke patients were significantly higher than those of PD patients in C1 but not in C2. For PD patients, the distance between thumb and index finger was more variable in C2 compared to C1 (i.e., TIF_{SD} was higher; p=.04), whereas for stroke patients no significant difference between conditions was observed.

3.3 C1 vs. C3: puzzle type

To investigate whether an image-based puzzle makes the AR game more cognitively challenging and more engaging, the task load, engagement, usability and task performance and execution were compared between C1 and C3.

For both patient groups, no significant differences were observed for: NASA-TLX overall scores; NASA-TLX Q1 (mental load); SUS; GEQ overall scores or any of the GEQ dimensions. In both conditions and for both patient groups, the five positive dimensions in GEQ had median values higher than 2.5, while for the two negative dimensions the median values were below 2.

Only for the stroke patients, *timeHandLost* was higher in C3 than in C1 (94 [64-105] vs. 39 [25-60] sec; Z=-2.50, p=.01), while no statistical differences were observed for *timeInteraction* and *timeNoInteraction*.

There was no significant effect of condition on any of the outcome parameters presented in Table 5 and Fig. 5**.** The use of an image-based puzzle (instead of colours) thus had no significant effect on movement characteristics.

3.4 C1 vs. C4: interaction modality

To explore if an easier interaction modality (i.e., pointing instead of grasping) affected user experience and movement characteristics, we compared task load, usability and task performance and execution between C1 and C4.

NASA-TLX, SUS, *noInteractionTime* and *timeHandLost* were not significantly different between C1 and C4. Only for stroke patients, *interactionTime* is shorter in C4 than in C1 (94 [72-122] vs. 114 [92-209] sec; Z=2.09, p=.03), while there was no difference between conditions for PD patients.

Analysis of the movement characteristics showed that, as expected, the change of interaction modality had effect on the grasping movement: TIF_{mean}, the distance between thumb and index finger, was larger for pointing (C4) than for grasping (C1). The reaching movement, however, was largely similar for both interaction modalities. Only for variability of the upper arm angle, there was a significant interaction between condition and group: due to a (non-significant) decrease from C1 to C4 for stroke patients, these patients showed larger variability of upper arm angle than PD patients in C1, but there no longer was a group difference in C4.

3.5 AR C1 vs. real world

Movements in AR took much longer than in the real world and were associated with lower maximum velocity of the upper arm, wrist and trunk (see Table 5 and Fig. 6). The AR movements were less direct to the target (i.e., a longer trajectory of the wrist). Moreover, AR movements were associated with larger trunk displacement than real world movements, especially for movements to contralateral targets (p=.003; while p=.38 for movements to ipsilateral targets). Variability of elbow angle and upper arm angle was reduced in the AR condition. For variability of upper arm angle, this effect of condition was less pronounced for the ipsilateral targets in the stroke group than for the contralateral targets in this group and for PD patients, as was evidenced by post-hoc analysis of the three-way interaction between condition, group and side.

Remarkably, no significant correlations were observed between characteristics of movements in AR C1 and movements in the real world. For movements in AR C1, however, some movement characteristics were related to usability and perceived task load. In specific, lower SUS scores (indicating lower usability) tended to be associated with a longer total duration (ρ=-.46, p=.06) and a higher TIF_{mean} (ρ=.60, p=.01). In a similar vein, higher scores on the NASA-TLX (indicating higher task load) were associated with a longer total duration (ρ=.59, p=.01), a longer wrist trajectory (ρ=.68, p=.003) and a smaller TIF_{mean} (ρ=-.72, p=.001).

Table 5. Significant results of the mixed ANOVAs for movement characteristics

	C1 vs. C2					**C1 vs. C3**				
	Factor	*Statistics*				*Factor(s)*	*Statistics*			
Time		*F-value*		*p*	η_p^2					
Total duration [s]	---	---				---	---			
Grasping										
***TIF*$_{mean}$ [cm]**	---	---				---	---			
***TIF*$_{SD}$ [cm]**	C×G	*F*(1,15) =	9.71	.007	.39	---	---			
Reaching										
Max elbow angular velocity [°s^{-1}]	---	---				---	---			
Max UA angular velocity [°s^{-1}]	C×G	*F*(1,15) =	9.54	.007	.39	---	---			
Max wrist velocity [ms^{-1}]	---	---				---	---			
Max trunk velocity [ms^{-1}]	G	*F*(1,15) =	6.61	.021	.31	---	---			
SD elbow angle [°]	C×G	*F*(1,15) =	4.80	.045	.24	---	---			
SD UA angle [°]	---	---				---	---			
Wrist trajectory [m]	---	---				---	---			
Trunk displacement [m]	G	*F*(1,15) =	4.82	.044	.24	---	---			

Table 5 (continued)

	C1 vs. C4					**C1 vs. real world**				
	Factor	*Statistics*				*Factor*	*Statistics*			
Time		*F-value*		*p*	η_p^2		*F-value*		*p*	η_p^2
Total duration [s]	---	---				C	*F*(1,12) =	176.3	< .001	.94
Grasping										
***TIF*$_{mean}$ [cm]**	C	*F*(1,16) =	11.89	.003	.43		NA			
***TIF*$_{SD}$ [cm]**	---	---					NA			
Reaching										
Max elbow angular velocity [°s^{-1}]	---	---				---	---			
Max UA angular velocity [°s^{-1}]	G	*F*(1,16) =	4.95	.040	.24	C	*F*(1,12) =	22.12	.001	.65
Max wrist velocity [ms^{-1}]	---	---				C	*F*(1,12) =	23.51	< .001	.66
Max trunk velocity [ms^{-1}]	G	*F*(1,16) =	7.16	.017	.31	C	*F*(1,12) =	33.00	< .001	.73
SD elbow angle [°]	---	---				C	*F*(1,12) =	10.04	.008	.46
SD UA angle [°]	C×G	*F*(1,16) =	5.08	.039	.24	C	*F*(1,12) =	36.93	< .001	.76
						C×S×G	*F*(1,12) =	5.76	.034	.32
Wrist trajectory [m]	---	---				C	*F*(1,12) =	13.61	.003	.53
Trunk displacement [m]	G	*F*(1,16) =	5.02	.040	.24	C	*F*(1,12) =	7.25	.020	.38
						S	*F*(1,12) =	11.82	.005	.50
						C×S	*F*(1,12) =	11.08	.006	.48

Effect size of the significant (p<.05) main effects and interaction effects (indicated by '×') was quantified as partial eta squared (η_p^2). Between-subjects factor: G (group; stroke vs. PD). Within-subjects factors: C (condition; as indicated) and S (side; ipsilateral vs. contralateral; for comparison C1 vs. real world only). Comparisons between AR conditions were based on n=10 stroke patients and n=8 PD patients, except for C1 vs. C2 (n=9 stroke patients and n=8 PD patients). Comparisons between AR C1 and real world were based on n=7 stroke patients and n=7 PD patients.

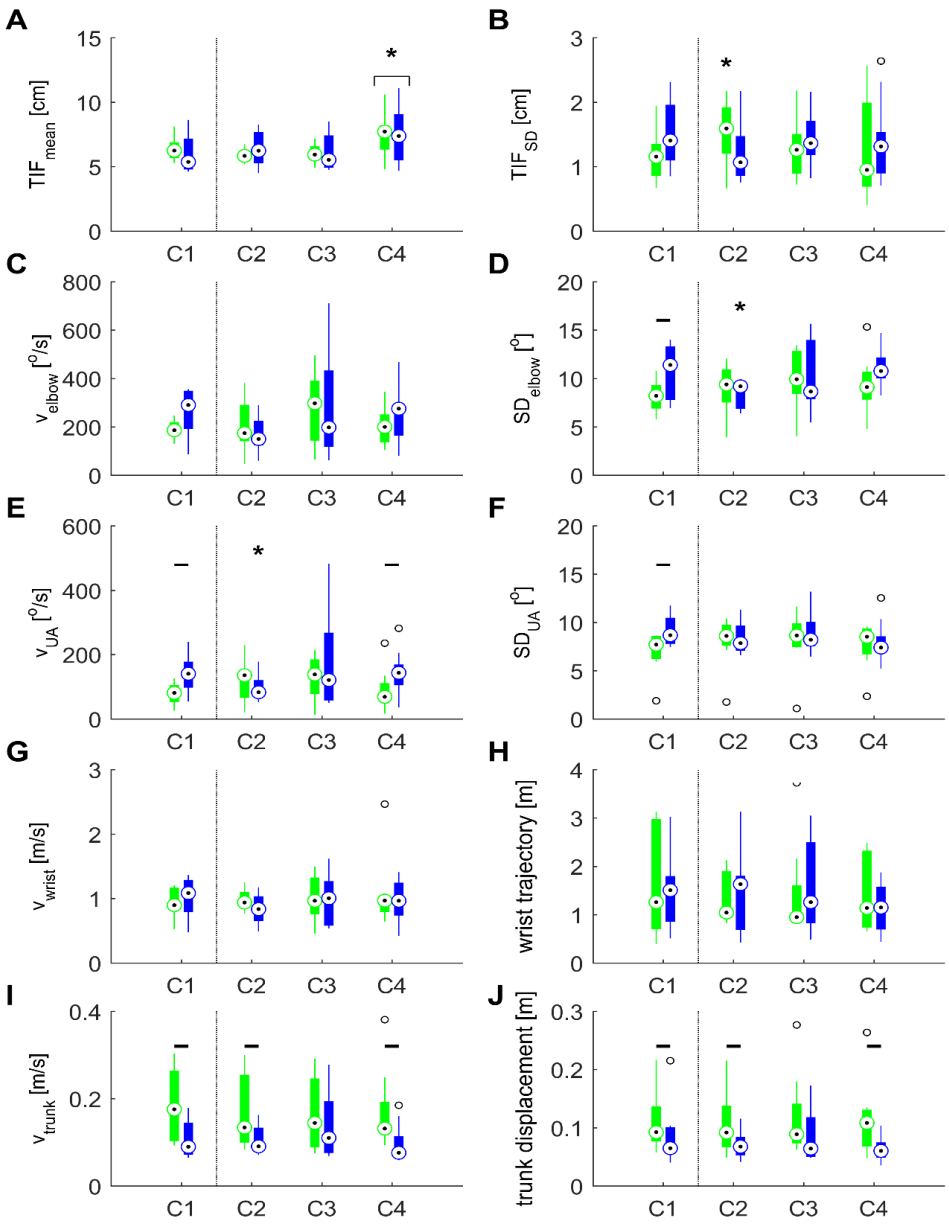

Fig. 5. Box plots of movement parameters for pairwise comparison between AR conditions. Green = PD patients; Blue = stroke patients; open circles indicate outliers; black dots indicate median values; asterisks (*) indicate significant differences compared to C1, the baseline AR condition (p<.05); horizontal lines indicate significant differences between patient groups (p<.05)

4 Discussion

We discuss the results of our study, based on the data presented in section 3, and also considering the feedback from patients in the debriefing sessions and our own observations during the experiment.

4.1 Usability of the AR system

As 76% of the SUS scores in Table 3 are below the threshold value 68, usability still needs to be improved.

The low usability scores seem to originate from two sources: *1)* problems with hand recognition and *2)* the small FOV of the HMD, which requires very good head-hand coordination to play the AR game. Despite these technological limitations, at least one patient in each group gave high SUS scores (see the bold lines in Table 3). These two patients experienced no problems with hand detection and managed to coordinate the movements of their head with those of their hands. As a consequence, they often only had one interaction episode per package (i.e., no loss of hand recognition while they were moving the package), where the distance between thumb and index finger was relatively stable around the prescribed value (i.e., $TIF_{mean} \approx 5$ cm; low values of TIF_{SD}). Both patients had a shorter total duration, a shorter interaction time and a shorter wrist trajectory than the other patients. For the PD patient (aged 59, mildly affected) movements in AR were characterized by pronounced involvement of the elbow (indicated by high v_{elbow} and SD_{elbow}) and little trunk displacement.

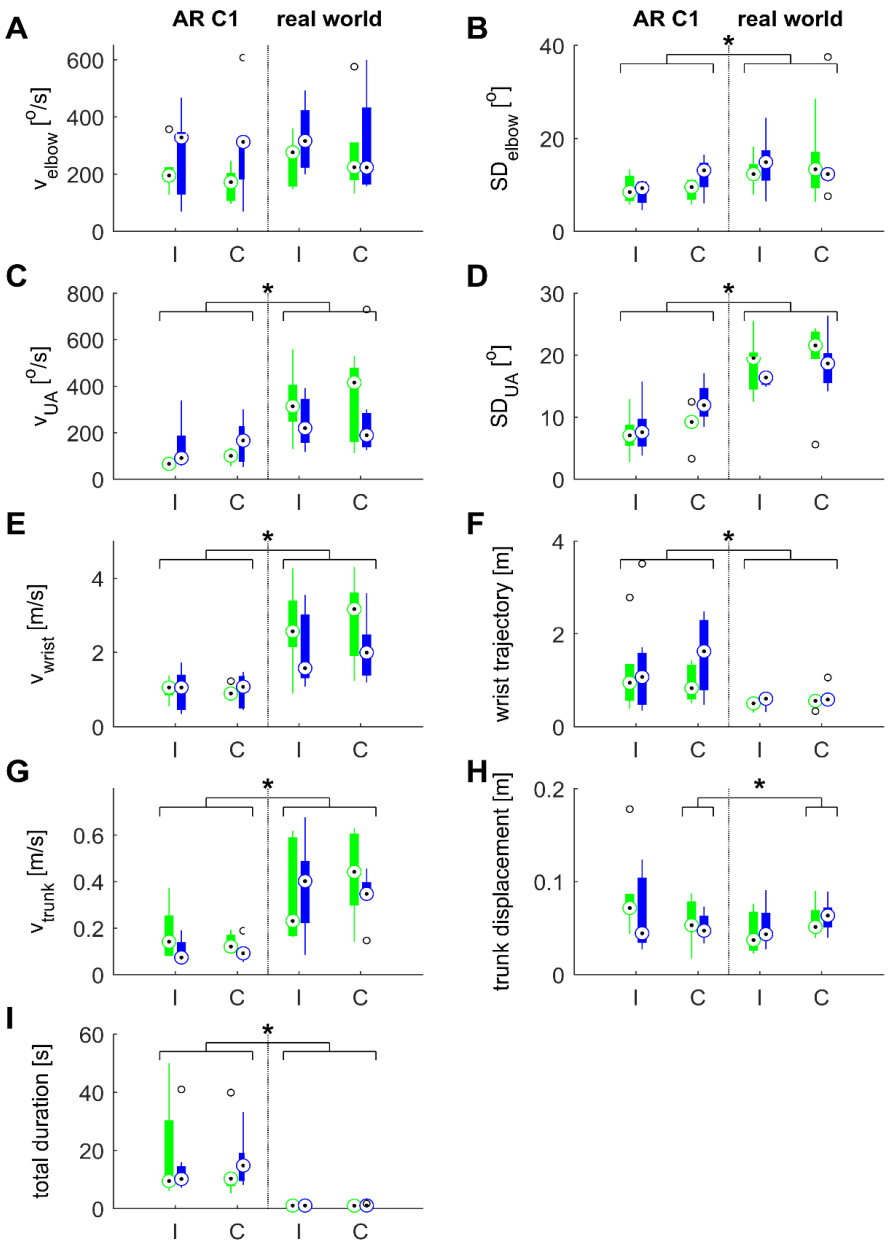

Fig. 6. Box plots of movement parameters for pairwise comparison between AR C1 and real world movements. Green = PD patients; Blue = stroke patients; i = ipsilateral targets; c = contralateral targets; open circles indicate outliers; black dots indicate median values; asterisks (*) indicate significant differences compared to C1, the baseline AR condition (p<.05); horizontal lines indicate significant differences between patient groups (p<.05).

In contrast, the stroke patient (aged 59, mild residual motor problems, 3 years after stroke) showed minimal involvement of the elbow (indicated by low values of velbow and SDelbow) and a pronounced trunk displacement. For both patients, movements in AR took slightly longer than in the real world. Importantly, for the PD patient movement characteristics were comparable for movements in AR and the real world (except that upper arm movements seemed less pronounced in AR). For the stroke patient, however, movements in AR were associated with less pronounced elbow and trunk movements and a shorter wrist trajectory than movements in the real world.

These findings suggest that the AR setup may be suitable for assessing the hand and arm function of mildly affected patients if the encountered usability issues, especially those related to hand recognition, can be overcome.

Despite the small number of participants in each group, strong correlations were observed between usability (SUS) and performance (perceived/measured) or engagement (GEQ) in some conditions, indicating that higher usability was associated with better performance end more engagement. In line with this, lower SUS scores (indicating lower usability) were associated with a longer total duration and a higher TIF_{mean}. Together, these findings suggest that usability is a key component for a good performance and also for the AR game engagement. Importantly, despite the current usability issues due to technological limitations, many patients showed their interest in this novel technology. Almost half of them even indicated that they would like to use the system frequently (9 out of the 20 patients gave scores in the upper half of the Likert scale for question 1 in SUS questionnaire [4]). These observations provide a positive signal for future developments.

4.2 Pairwise comparisons between AR conditions

Regarding the **virtual hand visual feedback**, our findings showed that especially PD patients seemed to benefit from the presence of the virtual hand, which was indicated by lower task load, higher SUS scores, and shorter *timeHandLost* and *timeNoInteraction*. Analysis of the movement characteristics further revealed that visual feedback of the hand enabled PD patients to keep a more constant distance between thumb and index finger while moving the virtual package. Also for the stroke patients, visual feedback of the hand led to a better hand recognition. Movements of elbow and upper arm tended to be more pronounced in the presence of a virtual hand.

Irrespective of the presence or absence of a virtual hand, both patient groups considered that the completion of the AR game was mentally and physically demanding, and that it required hard work to accomplish the game. However, patients did not feel stressed, perhaps because no time limits were imposed.

These findings indicate that, in general, the presence of a virtual hand was a better option for patients in the current AR setup. It is encouraging that patients were also able to perform the required tasks in the absence of this virtual hand. Further improvements of the alignment between the virtual and real content will eventually allow for removing visual feedback of the hand, so that patients only see their real hand in interaction with virtual objects.

Regarding the **puzzle type**, our findings showed that the effects of using of a themed image-based puzzle instead of a colour-based puzzle were negligible. Game engagement, task load, usability and movement characteristics were unaffected by the puzzle type. Perhaps, the task of associating a well-known touristic attraction to a country (e.g. Tour Eiffel to France) was too easy for the patients to improve engagement or increase task load. In future applications, subjects with different levels of difficulty from domains like history, geography etc. could be incorporated, to allow adaptation according to patient's performance.

Irrespective of the puzzle type, scores for the positive GEQ dimensions indicated a "moderate" engagement for both patient groups. At the same time, the low scores for the negative dimensions indicated that the AR game was not perceived as being "bad". Because good game experience is only possible if a game is easy to use, it is conceivable that the "moderate" engagement observed in the present study may partly be due to the relatively low usability of our system (see Table 3). Indeed, usability was strongly correlated with engagement (see Table 4; SUS, GEQ).

In contrast to our expectations, the **interaction modality** had no significant effects on task load, SUS score, *noInteractionTime* and *timeHandLost,* or movement characteristics other than TIF_{mean} (which was a direct consequence of the required hand posture for interaction). Only for stroke patients, a significant reduction of *timeInteraction* was observed for pointing compared to grasping.

Although it was anticipated that "pointing" would be easier than "grasping", these two hand gestures appeared to offer quite similar conditions for performing the required tasks in AR.

4.3 Pairwise comparison AR C1 vs real world

Although the movements in AR C1 and the real world were not exactly identical, it was expected that the calculated outcome parameters would be relatively insensitive to the small changes in start and target positions between AR and the real world. Nevertheless, large differences were observed for almost all movement parameters. For example, movements in AR took much longer and were less direct to the target (i.e., the total trajectory of the wrist was much longer) than movements in the real world.

It was anticipated that the patients who performed best in the real world would also perform best in AR. However, no significant correlations between movement characteristics in AR and the real world were observed. This finding suggests that performance in AR largely depends on other factors than pure motor function. Cognitive function, inexperience with AR, and issues with hand recognition probably play a large role in this regard.

4.4 Limitations of the current setup

The sensor for hand tracking was mounted on the HMD in an attempt to offer patients higher mobility and a natural way of interaction with the virtual world displayed in the OST-HMD. However, for this particular sensor the optimal position for hand recognition was with the palm oriented towards the HMD, which was experienced as a relatively unnatural position to grasp the package. Another limitation of the current setup was the relatively limited space for interaction. Because we used marker-based tracking of the environment, patients had to raise their hands in front of the HMD while they had to keep the A0 marker in view. The associated postures of the head and hand were difficult for some of the more affected patients.

5 Conclusion

In this work, we conducted a study on an AR game designed for assessment purposes of patients with upper arm motor dysfunction. We used contact-less hand tracking technology for interaction with the virtual content, which was displayed in the direct environment of the patients using stereoscopy. 8 PD and 10 stroke patients performed a reach-and-grasp task in four different AR conditions and in the real world, which provided us valuable information for objective evaluation of the current implementation and for further development of the AR system. A comparison of movement characteristics revealed that moving a real object was more targeted and took less time than moving a virtual object. Moreover, movements in AR were characterized by reduced variability (in angle and velocity) of the upper arm and more pronounced trunk displacement for ipsilateral targets. It is plausible that these differences are largely attributable to the difficulties that many patients encountered in achieving natural interaction with the virtual content. The usability of our AR system was relatively low. Still, 24% of the SUS scores were above the threshold value of 68 and, from our observations, these corresponded to the situations where the hand was correctly and robustly tracked (i.e., the hand was not erroneously identified as the contralateral hand and loss of hand recognition was minimal). This suggests that many barriers of the present prototype are due to technological limitations, rather than the AR setup itself.

Therefore, future work first aims at improving usability. As a first step, we will consider different sensors including data gloves for hand tracking to provide more robust hand tracking and more natural interaction, allowing recognition of more postures and gestures of the hand. In addition, we will enlarge the interaction space by means of multiple markers or natural feature tracking to offer more flexibility in the patients' movements. Enlargement of the interaction space will also be a necessary prerequisite for extending the capabilities of the current setup to full-body assessment, combining upper-body movement evaluation with gait analysis. Finally, we will consider using a Video See-Through HMD to achieve a more precise alignment of the virtual hand with the real hand, provided that patients do not get dizzy while wearing it. Also, the effects of Augmented Virtuality or VR for assessments of motor functions in different patient groups could be explored.

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