ArmAssist: a telerehabilitation solution for upper-limb rehabilitation at home

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***Abstract*—ArmAssist (AA), developed by TECNALIA, is a telerehabilitation platform aiming to help post-stroke subjects maintain the rehabilitation of the upper-limb at home. The AA includes robotic modules with multiple sensors to train and measure the users' voluntary movements. An assessment platform based on serious games is also included to not only engage the user but also perform automated evaluation of arm and hand function and their evolution over time. Moreover, the AA facilitates at-home rehabilitation with limited remote supervision by the therapist. In the present paper, the technical specifications and developments of the AA are described. Additionally, a summary of the outcomes of a usability evaluation of the AA is presented.**

***Index Terms*—Rehabilitation robotics, motion control, grasping.**

I. Introduction

STROKE is one of the leading causes of physical disability and economic burden worldwide. Most of the survivors after stroke live with long-term disabilities that demand intensive rehabilitation services. The paralysis of an upper limb is the predominant impairment after stroke and only 20-56% of them completely recover motor functions after 3 months of proper rehabilitation therapy [1].

Hence, systematic and long-term rehabilitation has been considered essential to improve the quality of life for post-stroke users. However, traditional rehabilitation programs require considerable time and effort from a therapist to both diagnose and treat each user repeatedly. Financial and staffing limitations commonly prevent therapy from reaching the frequency and intensity necessary for maximal recovery of lost functionalities. Over the last decades, several robotic systems for upper-limb rehabilitation have been developed as a means to reduce financial and clinical burden thanks to three important advantages over traditional therapy: the provision of higher intensity training, higher number of repetitions, and quantitative analysis of rehabilitation outcomes [2]. Robotic systems, such as Amadeo by Tyromotion [3], Armeo®Power or Armeo®Spring by Hocoma [4], or InMotion by BIONIK [5], can easily increase the number of movement repetitions, resulting in intensive therapies [6]. Intended for use in a clinical setting, the prevalence of these robotic systems is limited due to their cost, size, and the technical supervision needed, resulting in limited availability of the devices.

Best therapeutic outcomes are achieved by continuing long-term rehabilitative training, both to maintain recovered motor functions and to achieve further gains. For this reason, rehabilitation at home has been strongly encouraged where the users can freely adapt the sessions to their needs, while benefiting from higher motivation and engagement [7]. Sensor-based devices track users' movements. In addition, they are designed to help neurocognitive recovery using software platforms based on serious games [8].

This paper mainly contributes by presenting the technical details of the robotic ArmAssist (AA) system which is a telerehabilitation solution that has been initiated from the clinical and practical needs for home-based rehabilitation. The AA has specific features to facilitate home use due to the portable and safe design of the device, as well as a telerehabilitation platform that compensates for the limited supervision of the clinicians. The platform is based on serious games designed and developed in collaboration with therapists to engage the users in their rehabilitation. In the present manuscript a general overview of the system is described in section II. Hardware and the telerehabilitation platform are presented in sections III and IV, respectively. A summary of the usability evaluation outcomes is revealed in section V. The discussion and conclusions are presented in sections VI and VII.

II. System Overview

The AA combines a modular robotic system and an encoded table mat with a telerehabilitation platform based on serious games for upper-limb rehabilitation (Fig. 1.a). The compact design is cost-effective, portable, and specifically aimed for use at home. A regular table in the home environment is used to support the system's custom table mat where the lightweight (4 kg) robotic system is used to perform repetitive active movements for arm and hand rehabilitation. General system specifications are provided in TABLE I.

The modular design permits connecting and disconnecting different mechanical modules to provide arm, wrist, and hand rehabilitation, each individually or in combination. Numerous embedded sensors provide measures of active movements of the arm and hand. Arm position and orientation is calculated thanks to the camera installed in the robotic module which can read the DataMatrix (DM) codes printed in the table mat. The mat has been printed in laminated materials that will support dirt or liquid spill and can be easily cleaned. A rigid plastic plate has been designed and produced of Cestilene® HD-500, which can be used for rehabilitation of left- or right-side impairment. This plastic plate includes several boundary supports (i.e., hard stops) to prevent the robot from traveling

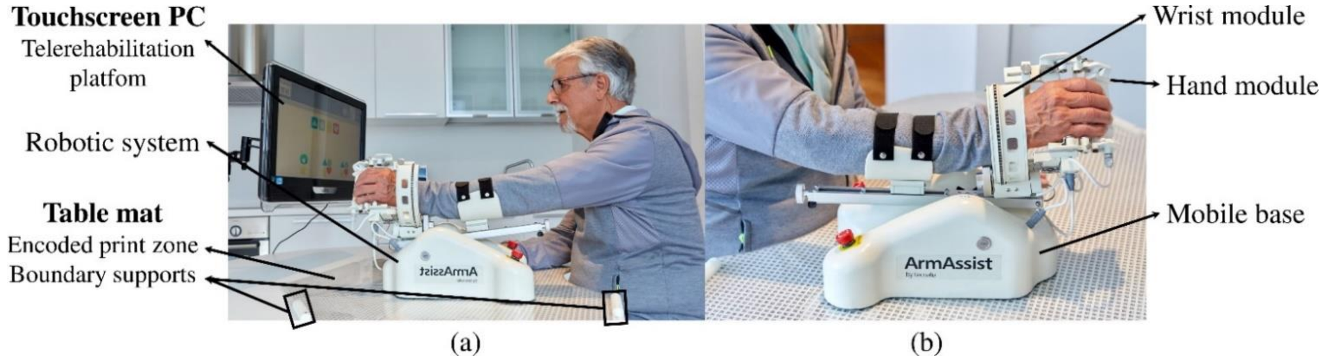

Fig. 1. ArmAssist (AA): (a) Overall view of AA consisting of a PC with telerehabilitation platform, robotic system, and table mat with the encoded print zone (DataMatrix codes including absolute position) and boundary supports for safety, and (b) robotic system of AA consisting of 3 submodules for arm, wrist, and hand rehabilitation.

TABLE I
AA SYSTEM SPECIFICATIONS

Module	Movement	Range
Mobile Base	Reacheable planar work area	69 x 110 cm
	Forearm tilt	-14° to 23°
	Vertical lifting force	0 - 20 Kg
Wrist	Prono-supination angle	-90° to 90°
Hand	Finger extension	0% - 100%

beyond the mat (Fig. 1.a). Kinematic information is then computed via algorithms explained in section III.A. The amount of arm support/lifting (i.e., vertical force) is also measured to monitor shoulder rehabilitation, and offer variable gravitational support of partial limb weight, as well as to impose loading levels above that induced by the weight of the arm itself [9]. In this way, the loading on the arm can be tailored to the ability of users and their recovery.

The robotic device also includes the option of using different hand modules. A hand module specifically developed for the AA at the University of Idaho allows active prono-supination of the wrist and hand grasping while measuring such motions in terms of angle and relative grasping forc e (Fig. 1.b) [10]. A simple orthosis for hand support can be used for those who cannot train grasping.

The AA's telerehabilitation platform is a software through which the clinicians can supervise and customize the therapy remotely. This software incorporates specific games for training as well as tasks for the assessment of motor function. The platform's serious games have been designed to increase motivation to train [11] while offering different training movements that can be carried out with the device to engage the users in their assigned therapy.

III. ROBOTIC SYSTEM

The robotic system is composed of three primary modules: 1) mobile base; 2) wrist; and 3) hand. Robotic components information is summarized in TABLE II.

A. Mobile base module

To facilitate not only the smooth 2D translational and rotational active motion of the forearm but also the weight compensation of the users' arm, a structure with three omni-directional wheels configured in an isosceles triangle on the base plate was designed to allow freedom of movement (Fig. 2.a). The main frame is attached directly to the base plate and the forearm bar where the attachment of an orthosis is mounted over the frame using a rotational joint. The fundamental structure and components are shown in Fig. 2.b. A custom PCB contains all necessary electronic components such as a microprocessor, a camera module, and Bluetooth classic module. The PCB collects all sensor data from the active movements of the user and wirelessly communicates with a PC in which the telerehabilitation platform is installed.

A special assembly consisting of the forearm bar, rotational joint, and 1-DOF force sensor allows natural forearm movement and progressive load training. The user's forearm is positioned in an orthosis on the bar (Fig. 1.b), which is connected to the module frame by a single-axis rotational joint whose angle is measured by a potentiometer to monitor elbow movement. The resulting design and omni-directional driving mechanism enable a person to conduct a natural and active forearm movement during planar reach tasks with minimal resistance. A 1-DOF force sensor is integrated between the base frame and the forearm bar, measuring the interaction force of the arm in the vertical direction. The forearm bar includes a single-button spring-loaded mechanism for quick attachment and detachment of the wrist module and forearm orthosis.

To detect the absolute position and orientation of the mobile base module, a sensor fusion technique is used. First, a camera built into a custom PCB takes a photo of DM codes printed on the mat. Each DM code has specific position information, and the captured DM code is decoded by a microprocessor, resulting in the absolute position of the module on the mat. The size of each DM code is 6 x 6 mm and the distance between the DM codes is 4 mm (Fig. 2.c). The opensource *libdmtx* library [12] is used to decode the DM codes and position resolution is obtained using the embedded software. The orientation of the module is measured by the

TABLE II
SUBSYSTEM COMPONENT SPECIFICATIONS

Module	Componet	Model	Features
Mobile Base	Microprocessor	RZ/A1H ARM® Cortex®-A9	Frequency: 400 MHz; Memory: 10 MB of on-chip SRAM
	Camera	OV5640C	Frequency: 15 fps; Output: 5 MegaPixel JPEG
	Potentiometer	Vishay 149	Linear resistance: 100Ω-2MΩ; Tolerance: 10%
	1-DOF sensor	Phidgets micro load cell	Capacity: 20 Kg
	Encoders	MILE	Resolution: 2048 CPT; Channels: 2
Wrist	Potentiometer	Vishay 536	Total resistance: 100Ω-100kΩ; Tolerance: 5%
Hand	FSR pressure sensors	FlexiForce® (Tekscan) A301 (thumb)	Force: 0-111 N
		FlexiForce® (Tekscan) A201 (4-fingers)	Length: 5 cm; Force: 0-111 N

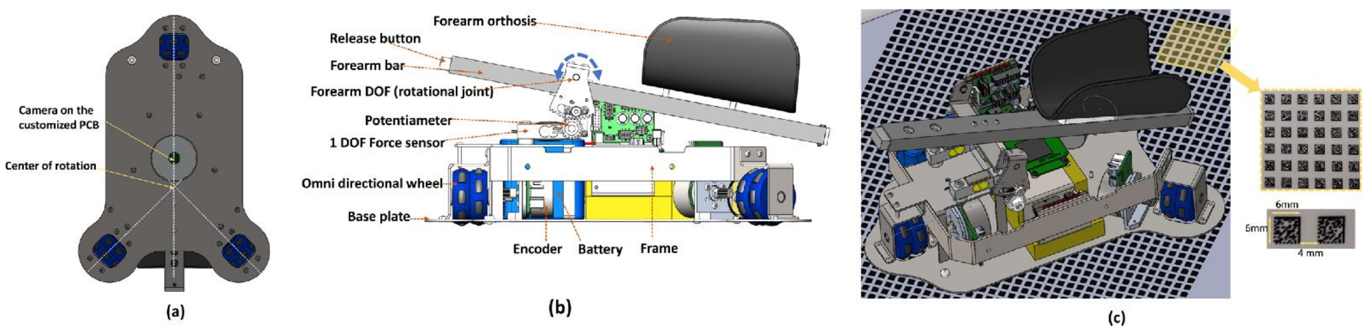

Fig. 2. Structure of the mobile base module: (a) configuration of three omni-directional wheels (view from bottom), (b) core components, and (c) perspective view with the mat containing DM codes.

angle calculation of the DM code with respect to the horizontal line in the captured photo. However, using DM code information alone produces a delay of 87-117 ms in the on-screen movement during game play depending on the DM image deformation due to the fast movements of the base module. To overcome this delay, the position and orientation of the module are estimated using a nonlinear Kalman Filter algorithm with simple rectangular gating [13] based on the signals of three encoders mounted along the axes of the omni-directional wheels. This sensor fusion algorithm allows for a faster position and orientation measurement done every 8 ms.

B. Wrist module

The wrist module for prono-supination training is attached on the forearm bar of the mobile base module (Fig. 3). The module allows frictionless active pronation and supination of the wrist through an assembly of two parallel semi-circular prono-supination guide links connected by standoffs and each sandwiched between 3 track bearings (1 inner, 2 outer) that are housed within the base assembly. A potentiometer connected to the rotational joint is used to measure wrist angle change measuring an absolute rotation angle through a custom semi-circular prono-supination gear with a transformed range of -90º to 90º. The wrist module also has a plate (Fig. 4) that facilitates the easy and quick exchange of the hand module for left and right sides. The pins under the base assembly and the spring mechanism inside the forearm bar enable quick mounting and dismounting of the wrist module with an one-button operation. This button also allows the position of the forearm orthosis to be adjusted according to the user's forearm length for improved comfort. A customized PCB that transfers the potentiometer signal to the main PCB in the mobile base module is also included.

C. Hand module

The hand module consists of two main submodules:1) a thumb module, and 2) a 4-fingers module, allowing the user to train active hand grasping and opening. To encompass a variety of hand sizes, the distance and orientation of the thumb module relative to the user's palm are adjustable by LJ1 and LJ3 in Fig. 4, while the 4-finger module allows variable distances between metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints (LJ2 in Fig. 4).

Both thumb and 4-finger modules have rotational joints with a torsion spring (RJ1, RJ2, RJ3, and RJ4 in Fig. 4) to help active opening of the hand. Force-sensitive resistors (FSR) are placed underneath plastic pads to measure the relative pressure that occurs when the hand is opened or closed. This pressure is used to measure functional aspects of the thumb and fingers. In the thumb, two orthogonal sensors are used to detect relative magnitudes of thumb force in each of two directions: 1) in the flexion/extension and 2) in the

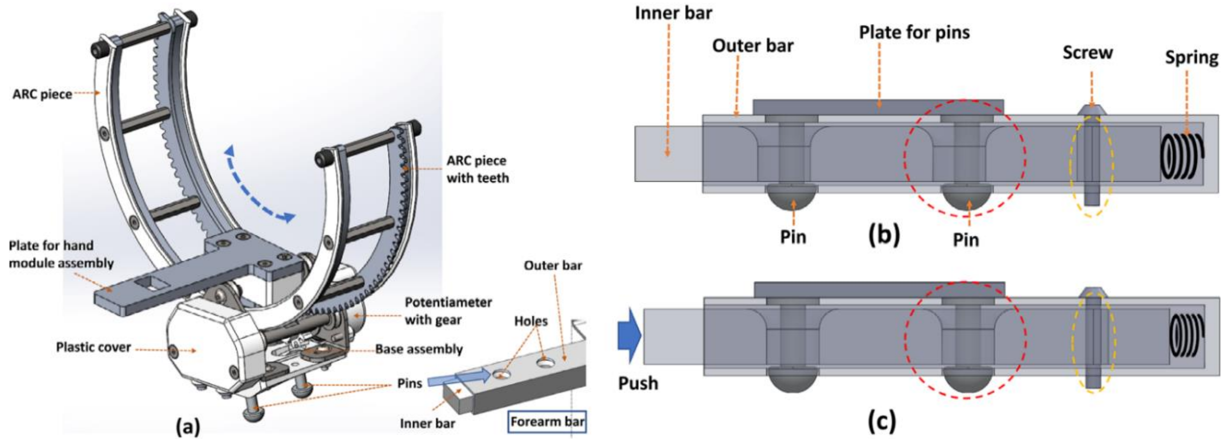

Fig. 3. Wrist module: (a) structure and core components, (b) and (c) an illustration of one button release mechanism. Thanks to rounded holes in the inner bar and spring, two pins of the module are simply inserted into two holes in the inner bar and then automatically locked (red circle in (b)). Pushing the inner bar (c) align the holes in the inner bar with those in the outer bar (red circle in (c)), resulting in quick and easy release. The movement of the inner bar is constrained by a screw (orange circles).

opposition/reposition. The latter is helpful in monitoring the level of undesired tone present in thumb adduction. Thumb mobility is supported by a passive single degree of freedom flexion/extension axis (RJ3 in Fig. 4) and a movable and lockable opposition/reposition adjustment [10].

The algorithm developed to process the FSR sensors data provides the quantity of pressure applied by the user and was successfully evaluated to determine the pressure applied by the thumb and the 4-fingers modules independently [10]. A strap with soft foam is used to secure the hand and prevent unexpected doffing of the module.

IV. Telerehabilitation Platform

Therapy with the AA is carried out in conjunction with a telerehabilitation platform based on serious games. This platform comprises 8 games for the assessment and 10 serious games for the training. Games have been designed to be easy to use and understand with the aim of supporting remote supervision by a therapist. Developed in collaboration with therapists and end users, the games are highly motivating to increase the user's engagement in training [14]. Additionally, they allow the therapist to adapt the training program to the user's needs and recovery level. The telerehabilitation software is a web-based platform that can be run under different browsers, and a standalone version for Windows has also been created for offline situations. In both cases, the platform has been designed to be used with touchscreens to avoid external peripherals and simplify the user experience. Games use data transmitted from the robotic system which are transferred from the robotic module via Bluetooth. The connection between the two is only made just before initiating game play to avoid inadvertent capture of movement data generated by the user/therapist during system setup.

A. Training configuration

The training for each person can be remotely configured by the therapist. The health professionals can assign a therapeutic plan of games and movements needed by the user. The therapist has access to a graphical evolution of the scores and performance indicators for each user to monitor rehabilitation progress and make adjustments when needed.

B. ArmAssist Assessment games

The ArmAssist Assessment (AAA) games provide an automatic and quantitative evaluation of arm and hand function. The AAA has been demonstrated to be statistically correlated with each of the three most significant standard clinical assess-ment tests: Fugl-Meyer Assessment, the Action Research Arm Test (ARAT), and the Wolf Motor Function Test [17]. The AAA games must be performed by the user at least once at the beginning to configure and adapt the training games and a periodic re-assessment is recommended to adjust the baseline to the user progresses. AAA games include the following main assessments:

- The active Range Of Motion (ROM) assessment allows the user's planar movement to set the ROM limits for all training games. The starting point is highlighted, and the user is asked to move along the indicated sector as far as possible without torso compensation (Fig. 5.a).
- Range Of vertical Force (ROF) assessment measures the capacity of the user to perform an isometric arm lift. The user first moves the mouse pointer (via arm motion) to the position indicated on the screen (one of the orange-colored circles) and then actively lifts the arm against the device weight as much as possible while maintaining the position. Green-colored circle size indicates the variation of measured lifting force (Fig. 5.b).
- Control Of the vertical Force (COF) for arm game (Fig. 5.c) quantitatively assesses the capacity of the person to lift the arm but in a relaxed position.
- Assessment of hand function (AHF) consists of two sub-assessments: prono- supination movement of the wrist and hand opening/closing (Fig. 5.d). The small rectangle in the gray arc moves as the user performs prono-supination movement with respect to the reference position (the center of the arc) and the reachable Range

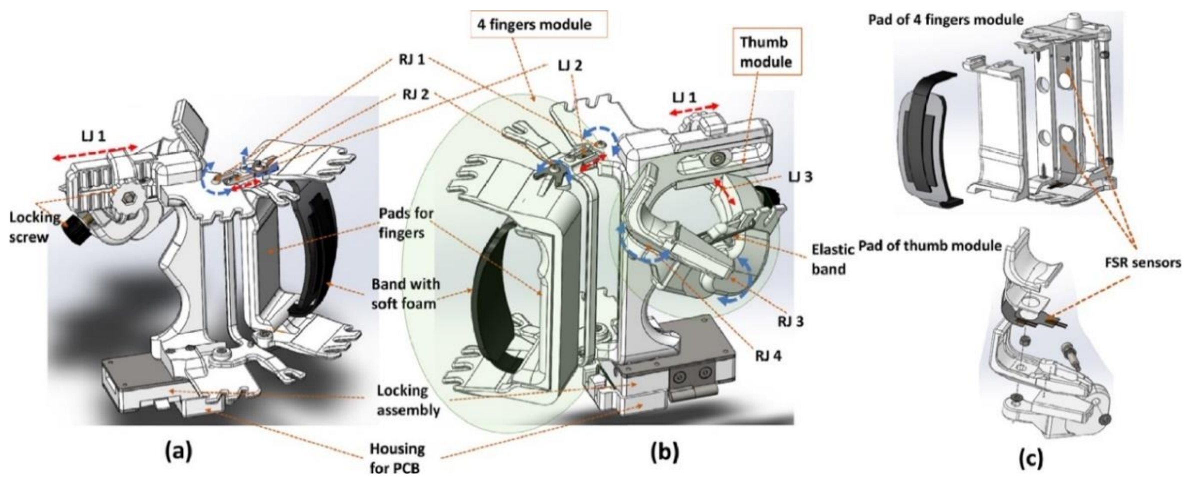

Fig. 4. Right-hand module: structure and core components. (a) View from the top of the hand, (b) view from the palm, and (c) detached views of the 4 fingers and thumb pads showing the location of the FSR sensors. Note: LJ = linear joint (red arrow) and RJ = rotational joint (blue arrow). LJ1: thumb for-aft position; LJ2: finger MCP-PIP distance; and LJ3: thumb opposition angle.

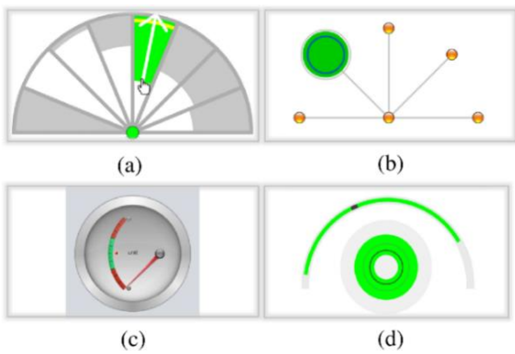

Fig. 5. AAA games (a) ROM (b) ROF (c) COF (d) AHF.

Of Prono-Supination (ROPS) is marked with a green-colored arc. The gray circle in Fig. 5.d is used to monitor the Range Of Finger opening and closing Force (ROFF). The pressure resulting from FSR sensors in the hand module changes the size of the circle to represent grasp and release function. The green-colored fields represent the wrist and hand motion capacity.

In the trials previously performed [14], [15] it has been observed that during assessment, users make a special effort to reach their maximum capability. The use of maximum values can be demotivating in training games because users cannot achieve those values consistently during the rehabilitation sessions. Hence, 70% of the maximum measured values from the ROM, ROF, and ROPS assessments apply to training games while 50% of the maximum value from the ROFF assessment achieve those values consistently during the rehabilitation sessions.

C. Training games

As stated above, 10 serious games have been developed for training. The games use the information transmitted from the robotic module to determine the position of a cursor on the screen which is relative to the calculated ROM in AAA. Each game targets different aspects of function so the platforms will offer only the games available for the movements to be trained, that are positioning on the table, suspension, grasp/release, prono-supination and the combination of them. The features of each game are explained below:

- Discover the picture presents an obstructed picture that is uncovered by the user during planar arm reach movements in each of 8 directions. Only positioning can be trained.
- Shopping Cart. The goal of this game is to pick up objects that appear on screen.
- Shapes. The user is asked to move objects located on the lower portion of the screen and pair them with their respective match in the upper portion.
- Memory game: the user is asked to find pairs of cards.
- Puzzle. Pieces must be assembled to complete the image.
- Words. Some letters of a word appearing are missing and the user is asked to complete the word.
- At the bar. The user has to take the bottle and fill in the glass through the coordination of both grasping and prono-supination movements.
- Solitaire. The user has to complete the solitaire by placing the cards in the correct place. This game is recommended for users with relatively high dexterity and long concentration. At least 5-10 min are required.
- Online games. Existing online games can be played using the robotic system as a mouse.

Each training game, except for the online games, has 5 levels of complexity that are automatically updated based on the evolution of the user or manually by the therapist. The higher the level is, the higher involvement of motor and/or cognitive function is needed.

V. Usability Evaluation

The AA has been designed to facilitate robotic-assisted rehabilitation at home, allowing the user to continue effective therapy with low supervision while maintaining safety. The

AA was evaluated in multiple clinical settings; results show that it is well accepted by therapists and users, and makes the therapy more enjoyable and motivating [15], [16]. An improved version in terms of robustness and aesthetic features, has been evaluated by two different studies performed in Spain [17] and the Netherlands [18] respectively, which was supported by MERLIN EIT Health project. The study was approved by the local ethics committee and competent authority of each site.

Twelve stroke subjects were recruited from each country, resulting in 24 users in total. Three subjects in Spain dropped-out from the study due to the COVID-19 situation, while 1 from the Netherlands abandoned the study after 3.5 weeks of rehabilitation with the AA. In both studies, the AA was installed at the subjects' homes. System Usability Scale (SUS), Intrinsic Motivation Inventory (IMI), and Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST) scales were used to evaluate the usability, acceptance, and user experience. Study main results are shown in TABLE III.

Additionally, semi-structured interviews with therapists and users were carried out. Most of the participants reported that they were interested in using the AA for a longer period, and that they would recommend its use to others. Participants also enjoyed the freedom in determining when, where, and for how long they do the training sessions with the AA. The device was also considered easy to understand and use. Although they commented that the mobile base module is a bit bulky, participants felt comfortable and confident using the system.

VI. Discussion

While the functionality and usability of the AA have been well accepted by therapists and patients through clinical trials, some recommendations have been proposed. It has been noted that AA wheels can smeared the mat due to friction when the AA system is used for extended periods, resulting in additional delay in the absolute position and orientation update because DM images are not sufficiently clear. Hence, the mat must be periodically cleaned with a wet wipe by the user. After long periods of time, it may be necessary to replace the mat or wheels which get damaged or dirty with long-term use. On the other side, the use of a camera for position detection requires a somewhat bulky dome to read the DM properly due to the distance needed between the camera and the mat. However, this technology was selected for its cost effectiveness. Changing the technology used for the calculation of the position in the plane could result in a smaller device and remove the mat component.

The inclusion of wrist and hand modules were highly valued for rehabilitation of prono-supination and hand grasping/opening. Nevertheless, the rehabilitation of wrist flexion/extension has also been required by some clinicians, so a new design of the module could be developed to include these movements.

In a new, enhanced version, the functionality of the AA has been extended by including motors in the mobile base. In this way, the AA can provide active assistance that is necessary to rehabilitate subjects with severe impairment in the acute phase that cannot otherwise perform the active shoulder and elbow movements needed for rehabilitation. The presented non-motorized module is deployed for home-use, while a motorized module has been proposed for rehabilitation facilities under clinician' supervision to ensure safety while allowing consistent rehabilitation throughout the entire period of therapy.

VII . Conclusions

The AA is an at-home rehabilitation solution that includes a robot that measures the active movement of the arm, wrist, and hand grasping, is supported by a telerehabilitation platform based on serious games for assessment and long-term training. AA consists of a portable robotic module and dedicated software that can be easily installed on any PC or tablet to be used at home. The AA has been tested by real users, demonstrating both clinical effectiveness and acceptance of the system, with several minor recommendations for improvement. A combination of AA technologies with advanced ICT is anticipated to accelerate the proliferation of rehabilitation at home while facilitating intelligent, safe, and self-adaptation of the system to users' capabilities and training preferences.

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TABLE III
Usability Evaluation: Demographic and Results

Usability test results	**The Netherlands**	**Spain**
SUS (0-100)	77.27±16.1	71.94±16.38
QUEST (1-5)	3.90±0.39	3.81±0.38
IMI (1-7)*		
Interest	5.5±0.50	6.0±1.82
Usefulness	6.5±0.17	6.1±1.93

*Results of IMI in the Netherlands was calculated with N=10 because one of the participants was unable to complete the questionnaire.

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