ArmAssist: development of a functional prototype for at-home telerehabilitation of post-stroke arm impairment

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Abstract – Growing numbers of stroke survivors are leading to increasing numbers of motor deficits, the majority of which include deficiencies in arm function. There is a strong need, therefore, to find new tools and strategies for providing efficient and effective sub-acute patient care. The requirements for such a device are outlined from both patient and therapist perspectives, and a new prototype system for sub-acute arm training in post-stroke care is presented. The complete system is composed of a base module with quick-connecting hand and forearm orthoses, a global position detection mat, and an all-in-one touchscreen PC with telerehabilitation software and interfaces. The size and portability of the system allow it to be easily moved and setup in the patient home to enable increased durations and intensity of training outside of the standard in-clinic care.

Index Terms – ArmAssist, arm rehabilitation, stroke rehabilitation, training at-home, telerehabilitation.

I. INTRODUCTION

New technologies to address motor deficits from stroke and other sources of arm impairment are needed. Considering (1) the increasing trends in stroke, (2) the known benefits of higher training duration, and (3) the existing devices in rehabilitation, it is expected that simple and low-cost solutions can provide the missing key to improve long-term frequency and duration of patient care. The solution lies in the development of simple and modular tools for clinical and at-home rehabilitation training. Providing patients with better tools for training at home both increases the ease of patient access to healthcare and also reduces the strain on the healthcare system.

Each year in the United States alone, 780,000 persons suffer a new or recurrent stroke. This adds to a combined sum of nearly 6 million persons currently living with the long-term effects of a prior stroke [1]. Improved medical treatment of the complications caused by acute stroke has contributed to decreased mortality, but 90% of the survivors have significant neurological deficits. Impairments in the upper limb tend to persist long-term with only 14-16% of stroke survivors with upper extremity hemiparesis regaining complete or nearly complete motor function [2]. Although the effects of stroke depend largely on the location of the obstruction and the extent of the brain tissue affected, movement disorders and stereotypic muscle synergies affect most individuals with stroke [3, 4].

A review of the current standard of care shows that there is no single technique that occupational and physical therapists implement to improve upper extremity function, many of the techniques utilized require some amount of manual assistance from the therapist in order to position, guide, and support all or some of the limb weight [5]. Even with only partial compensation of gravitational forces, it is possible for patients to perform controlled movements that they could not otherwise perform without assistance [6]. The training typically begins during the early sub-acute phase of stroke when the patient develops sufficient muscle tone and trunk stability to support sitting in a chair and commanding the device for the duration of a 30- to 60-minute training session.

With robotic-assisted interventions, studies have shown that patients who perform progressive resistance exercises as little as 3-4 times per week for 6-12 weeks can improve both in strength and function [7]. Furthermore, recently published research work confirms that better results in terms of rehabilitation outcome are obtained in specialized care centers where patients receive more therapy per day for extended periods of time [8].

The aim of this research is to develop a simple device that is portable, modular, easy to use, and that includes only the essential components necessary to enable effective telerehabilitation. After a period of clinical training, when the therapist feels the patient is able to use the system with minimal manual assistance, the system is sent to the patient home where the patient can continue training under the remote supervision and guidance of the therapist. It is believed that a basic, low-cost system will produce the greatest outcome in terms of the number of patients treated while producing functional gains comparable to more complex systems.
The prototype rehabilitation system presented in this paper is the second version of the ArmAssist. The first prototype (Fig. 1 - left) has been previously presented [9] as well as the method of absolute position measurement used [10]. The second generation prototype (Fig. 1 - right) builds from the lessons learned in the first version, extending the system’s usability and functionality.

II. SYSTEM REQUIREMENTS

The requirements of the system were iteratively developed from numerous clinical interviews, expert focus groups, and pilot tests with patients and therapists. A brief summary of the resulting requirements is formulated in Table I. In the table, requirements have been grouped by the categories of usability, functionality, and safety.

A. Requirements for Usability

The usability requirements considered in the development revolved mainly on the patient in the home environment as the primary user and are summarized in the top panel of Table I. Eight requirements were identified as being of primary importance for the patient including aspects of system size, adjustability, and ease of use. Ease of use aspects such as donning the device and understanding the system charge state applies equally to patients as well as therapists although the patient dons the device himself whereas the therapist puts the device on the patient. The therapist is able to use both hands in placing the user limb and securing the fixation, whereas the same should be doable by the patient at home using only his healthy limb to assist in fastening the device. An important consideration for in-clinic use was that the therapist should be allowed to stand close to the impaired shoulder in order to assist the patient during their in-clinic training. Three areas were identified as pertaining to both patient and therapist and also both clinical and home environments. These were related to system start-up time, ease of donning/doffing, and complexity of setup and takedown. A low start-up time for the patient means minimal steps to patient logon and therapy access, whereas for the therapist it includes quick orthosis size selection and adjustment.

B. Requirements for Functionality

The functional requirements are more evenly distributed between needs of the therapist and needs of the patient. For the patient, the primary concerns are related to the allowable workspace and the ease of movement in the passive system. For the therapist, the requirements were placed on the measures needed to provide quantitative reports of performance. Although the wireless portability has not been expressed as a critical need for either the patient or the therapist, it is considered a feature that would increase the versatility of use in the home environment and therefore was included. A great deal of interest was expressed in modules for hand functionality; although this has not been the present focus of development, a requirement of having a quick mechanism for connecting and disconnecting the orthoses was put as a priority in order to enable such add-ons in the future as well as serve to speed setup time in the clinic.

In short, the design should (1) provide a large workspace for the user, (2) provide low resistance movement support, (3) provide a quantitative measure of force and movement tracking for computation of performance metrics, and (4) be able to run on a single charge for a full workday in the clinic or one week in the patient home.

C. Requirements for Safety

Safety requirements fell within the range of standard safety concerns, i.e., prevention of tips, falls, shocks, pokes, and pinches, and one specific to the patient population about shoulder support. It is know that the patient population has a tendency for shoulder injury such as subluxation due to the severe loss of muscle tone following stroke. Many patients wear a shoulder harness in their daily life outside of the clinic for this reason. It is necessary, therefore, in a therapeutic rehabilitation robot for arm training to provide adequate support to not only the hand, but also the forearm closer to the elbow in order to reduce the gravitational pull on the shoulder joint.

III. ARMASSIST HARDWARE DESIGN

A. System Overview

The complete ArmAssist system for telerehabilitation (Fig. 2) is composed of a wireless mobile base module, a global position detection mat, a PC with display monitor, and a telerehabilitation software platform. The system allows therapists and patients to engage in telerehabilitation training from independent locations given the availability of at least periodic internet connectivity. The system must be setup on a flat surface and it is considered that an existing table in the patient’s home environment will be utilized.
TABLE I. FUNCTIONALITY, USABILITY, AND SAFETY REQUIREMENTS FOR A PORTABLE ARM REHABILITATION SYSTEM BASED ON A WHEELED MOBILE BASE MODULE.

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Specification</th>
<th>User/Target</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forearm length adjustability</td>
<td>5 sizes (15 mm increments)</td>
<td>x</td>
<td>Length adjustability from the 1st percentile female to 99th percentile male.</td>
</tr>
<tr>
<td>Hand size adjustability</td>
<td>3 sizes</td>
<td>x</td>
<td>Hand and forearm orthosis sizing through custom orthoses built from three size templates.</td>
</tr>
<tr>
<td>Low start-up time</td>
<td>&lt; 30 sec</td>
<td>x x x x x</td>
<td>Therapist: time to select patient sizing, attach patient, and start session. Patient: login and entry time.</td>
</tr>
<tr>
<td>Battery/charge indicator</td>
<td>Full/mid/low charging/charged</td>
<td>x</td>
<td>External indication of battery level and charge status.</td>
</tr>
<tr>
<td>Ease of donning/doffing</td>
<td>one-handed donning/doffing</td>
<td>x x x x x</td>
<td>Patient able to attach arm to system with only the help of his/her healthy limb.</td>
</tr>
<tr>
<td>Small device size and weight</td>
<td>&lt; 3 kg base unit</td>
<td>x</td>
<td>Base module weight of no more than 3 kg.</td>
</tr>
<tr>
<td>Home-compliant</td>
<td>fit existing table space</td>
<td>x</td>
<td>In-home set up with existing household environment.</td>
</tr>
<tr>
<td>Therapist proximity to</td>
<td>maintain arm contact with good posture</td>
<td>x x</td>
<td>System enables the therapist to stand in contact with the patient limb in order to guide and assist.</td>
</tr>
<tr>
<td>System setup and takedown</td>
<td>&lt; 2 min</td>
<td>x x x x x</td>
<td>System setup or take down by trained person in less than 2 minutes.</td>
</tr>
<tr>
<td>Large planar reach workspace</td>
<td>0.5 m^2 supported 0.3 m^2 measured</td>
<td>x</td>
<td>Forearm support over 0.5 m^2 zone and arm measures taken over 0.3 m^2 zone.</td>
</tr>
<tr>
<td>Low rolling resistance</td>
<td>&lt; 2.5 N static</td>
<td>x</td>
<td>Low resistance to movement in both static and rolling conditions.</td>
</tr>
<tr>
<td>Global position/orientation</td>
<td>+/- 10 mm (+/- 5 deg)</td>
<td>x</td>
<td>Global position detection accuracy to within 10 mm and orientation accuracy of 5 degrees.</td>
</tr>
<tr>
<td>Vertical force measure</td>
<td>+/-98 N (+/-0.1 N)</td>
<td>x</td>
<td>Maximum force of 98 N with precision of 1%.</td>
</tr>
<tr>
<td>Communication protocol</td>
<td>wireless</td>
<td>x</td>
<td>Uses wireless communication technology such as bluetooth.</td>
</tr>
<tr>
<td>Rechargeable battery</td>
<td>5000 mA-hr, 10-hr continuous use time</td>
<td>x x</td>
<td>Rechargeable battery with a continuous use time of at least 10 hours.</td>
</tr>
<tr>
<td>Easy add-ons</td>
<td>quick (2-sec) connect mechanism</td>
<td>x x</td>
<td>Capacity for quick and easy add-on modules to extend functional training to the hand.</td>
</tr>
<tr>
<td>Anti-tip stability</td>
<td>primary and secondary bases of support</td>
<td>x</td>
<td>Resistance to overturning with applied pronosupination torques should be provided through weight and secondary base of support.</td>
</tr>
<tr>
<td>Shoulder/forearm vertical</td>
<td>proximal forearm orthosis</td>
<td>x</td>
<td>Reduced risk of use injury or shoulder subluxation during extended arm training.</td>
</tr>
<tr>
<td>Device fall prevention</td>
<td>lateral and posterior safety stops</td>
<td>x x x</td>
<td>Reduced risk of inadvertant fall from edge of table.</td>
</tr>
<tr>
<td>Minimal risk of shock</td>
<td>low-power, wireless technology</td>
<td>x x</td>
<td>Negligible risk of electric shock due to on-board power supply and wireless technology.</td>
</tr>
<tr>
<td>Ergonomic orthoses</td>
<td>adaptable shape and sizing</td>
<td>x</td>
<td>Comfortable and secure orthoses to maintain hand and forearm position with respect to device.</td>
</tr>
<tr>
<td>Ergonomic points of contact</td>
<td>rounded edges without pinchpoints</td>
<td>x x</td>
<td>Eliminated pinchpoints and unsafe edges that could contact user during system use.</td>
</tr>
</tbody>
</table>
Figure 2. The ArmAssist telerehabilitation system components include: the PC with monitor, a telerehabilitation training software, the wireless mobile base module, and the global position detection mat. CAD mock-up shown in the image includes a height-adjustable table currently in use in one of the consulted clinical centers.

B. Wireless Mobile Base Module

The internal structure of the wireless mobile base unit (Fig. 3) is composed of an aluminum structural frame, an integrated pcb, a 1-dof force sensor, and a quick-connect forearm assembly.

Structural frame - The structural frame is an assembly of custom aluminum brackets designed to house three omni-directional wheels (Kornylak, FXA315), the force sensor, and connect the various other components that make up the assembly. In addition to holding the assembly together, the structural frame has 2 primary purposes: 1) to support loading in the vertical direction, the forces of which are transferred to the wheels, and 2) to minimize the bending moments applied to the wheel brackets. Even small misalignments of less than 0.5 degrees between the wheel axis and floor yield noticeable vibration in movement performance. For this reason it was important to consider alignment errors not only from deflection forces, but also from other sources. The majority of parts in the structural frame are formed through a bending process which leaves angle and position errors in assembly alignment. To reduce the effects of residual alignment errors in the sagittal and coronal bend planes, the plantar side cover plate (shown in Fig. 3) is used in conjunction with the frame to secure the position and orientation accuracy of the wheel alignment.

1-DOF force sensor - A force sensor (Fig. 3) is integrated between the structural frame and the forearm assembly, measuring all user interaction forces in the vertical direction. The measure of vertical support provided by the device is considered a critical factor in progressive load training, where the goal is to gradually reintroduce gravity into the planar workspace of patients with gravity-induced dis-coordination. The force sensor has a 10 kg load capacity in both upward and downward directions.

Integrated PCB - The main activity of the integrated PCB (Fig. 3) is monitoring readings from system’s measurement sensors and communicating these signals wirelessly to the desktop PC. Integrated hardware on the board includes 3 optical mouse sensors (Avago Technologies, ADNS-3080), a bluetooth module (Free2move, F2M03GXA), and a microprocessor (STMicroelectronics, STM32F103RB). The optical sensors (figure 4 - right) are arranged linearly with an equal spacing of 60 mm between each sensor, where the two outermost sensors are used to detect relative changes in position and orientation at 25Hz, and the central sensor is used as a camera to send images of the mat surface at an average rate of 3.3Hz. In addition to the 3 on-board mouse sensors, the PCB monitors readings from the 1-dof force sensor (Fig. 3) as well as the orientation of the forearm dof by means of an analogue potentiometer (Vishay, 149SXG56S103SP) with a 6:1 gear reduction. Powered by a 5000 mA*hr rechargeable battery (BPI, LC3262+PC), the system achieves a continuous operating time of up to 20 hours. An automatic standby mode is entered after 5 minutes of inactivity extending the idle life of the battery up to 500 hours.

Forearm assembly – The forearm assembly is composed of a forearm bar with a custom-designed quick-connect mechanism, and a set of brackets that allow the bar a single degree of freedom. The axis of motion is oriented parallel to the table surface and acts perpendicular to the long axis of the forearm at a point proximal to the wrist (see Forearm DOF in Fig. 3) while a spring acts to provide an amount of vertical support to the elbow. The resulting design enables the forearm bar to follow the user’s natural forearm movements during planar reach tasks with minimal resistance. The quick-connect mechanism enables rapid changing of hand and forearm orthoses between sizes, quick adjustment of forearm support position for arm length
Figure 4. A base module quick connect system allows rapid selection and placement of orthoses for the hand and forearm (left) and easy 1-button orthosis removal (right).

differences, and easy switching between left- and right-handed orthoses. For convenience, the orthoses can be secured to the forearm bar simultaneously or one by one (Fig. 4 - left), and can be removed by pressing a single button located at the distal end of the forearm bar (Fig. 4 - right).

C. Global Position Detection Mat

The global position detection mat is composed of a high density polyethylene sheet with a high resolution laminated print mounted to the top.

The sheet is made in a rigid 10mm thickness to minimize bending under the weight of the user in the regions that are unsupported from below by a table. A 360-mm diameter cutout allows the mat to wrap around the patient on both left and right sides to improve repeatability of positional collocation between patient and workspace, and also to provide support to the mobile base module in the lateral regions when the patient is at rest. The overall dimensions were adapted from a similar table surface in use at one of the collaborating clinics where a cardboard surface had been used to provide lateral arm support to patients during their clinical training.

The laminated print is encoded with a central grid (512mm x 288mm) of 16 (4x4) positional zones (Fig. 5a). Each zone contains a repeated 2-symbol pattern (Fig. 5b) that can be captured with a single camera frame from the base module’s central optical sensor in any position or orientation of the device, provided that the camera resides fully within one of the 16 zones. The resulting accuracy of the detection algorithm yields an average absolute position error of 6 +/- 3 millimeters and an angular error of 1.2 +/- 1.4 degrees.

Mat versions have been created for both clinical (Fig. 5c) and at-home use (Fig. 5d) where the clinical version contains two additional semi-circular cutouts, one on each side, to allow the therapist to be able to work closely with the patient from either side of the table.

D. PC and TeleReha Software

The platform is developed in a modular way to be easily extendable to a variety of rehab devices, and is designed to support the phases of therapy planning, training, and assessment. Details of the functionalities supported in the platform are further described in [11]. In the game interfaces, a distinction is made between games for assessment and games for training. Assessment games are short (1-2 minute) tasks that involve a targeted movement with defined parameters, while training games span longer timeframes to fill the majority of training time.

Assessment games are designed to provide the clinician with an objective assessment of the range of movement, vertical support trajectories and point to point movements. Training games, on the other hand, are composed of more complex tasks and exercises that may last typically from 5-15 minutes, and provide more entertaining or challenging environments. They can include more complex cognitive components integrated along with motor tasks in order to motivate and engage the subject. Among various cognitive aspects considered, current training games incorporate problem resolution though jigsaw puzzles and card games, memory recall tasks through classic memory games, and language skills in a word completion game.

General performance indicators are stored for each session and every game. For the assessment games also full force and trajectory information are stored in order to allow for a more detailed post-analysis by the therapist. In the event of limited or no network coverage, the platform has both online and offline training and data storage modes. As a result, training data can be stored locally on the hard-drive and synchronized with the central server when network connectivity is available.
Training tasks are displayed on a 21.6-inch all-in-one touchscreen PC (ASUS Eee Top ET2203) as shown in Fig. 5c.

IV. DISCUSSION

The ArmAssist hardware and TeleReha software are involved in ongoing studies of clinical and domestic usability at Hospital La Fe in Valencia and the Guttmann Institute in Barcelona. The target outcome of the studies is to assess the applicability and usability of the hardware and software user interfaces for both patients and therapists. The system has also undergone pilot testing in a variety of smaller local centers, representing both the private and public sectors; outcomes have been very positive and met with high levels of interest in all cases. In some cases, therapists have found the system to help motivate patients to perform levels of exertion beyond what is normally achievable during their session. In other cases, patients themselves have expressed gratitude for the opportunity to use the system, commenting on the higher level of entertainment experienced during training as compared to their standard exercises. A further indicator in patient interest is evident from their requests for specific additional game genres, such as car racing.

While the system is highly portable by market comparison, there remains room for improvement, particularly in overall weight. The all-in-one PC although nicely packaged with touch, sound, webcam, and microphone, weighs 8.9kg. The mat’s 6.5kg could be lowered as well. The large screen size of the PC, on the other hand, helps patients to see the tasks clearly and to engage them in the task exercises. Furthermore, the screen size has been reported by many therapists as providing a significant contribution to the patient experience and some have even discouraged reducing its size to that, for example, of the iPad. System attributes that have been considered for revision or inclusion are additional modules to extend the functionality of the system to a greater array of pathologies and over a greater portion of the rehabilitation timeline.

IV. CONCLUSION

The second-generation prototype of the ArmAssist arm rehabilitation system has been developed. The target application is for at-home continuation of clinically-prescribed arm reach exercises. A complimentary telerehabilitation platform and set of games for training and assessment have also been developed in parallel. The systems have been developed following a close collaboration with clinicians and therapists to ensure a good match between technology development and real clinical need. Initial feedback from usability testing indicates the system may be beneficial in both extending training duration and increasing the intensity of practice for post-stroke arm deficits during standard in-clinic care as well as for post-discharge telerehabilitation from at home.

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