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Towards an Affordable Assistive Device for Personal Autonomy Recovery in Tasks Required of Manual Dexterity

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ABSTRACT This paper reviews the results of a challenging engineering project that arose with the goal of implementing an electromechanical, automatic, portable, and inexpensive device. The device should be able to assist people who lack of dexterity in their hands to use small tools and everyday utensils, such as scissors or tweezers. In this paper, the hardware development and software functionality are described. The original specifications were developed to implement an affordable functional prototype able to serve as a low-cost assistive technology. Several commonly used electronic devices were integrated to create an innovative application. A simple mechanical system based on gears and a worm screw is used to convert the stepper motor rotation to a linear movement on the device tip. A tool-oriented control to increase the device usability was designed through two simultaneous communication channels: touch-screen and smartphone app. Pilot trials were conducted at healthcare facilities to evaluate the technical feasibility, the obtained functionality, as well as the device acceptance by target users. Based on user experience design, the app functionality was enhanced and subsequently tested. Finally, a review and reformulation of the specifications of the original design were accomplished. These changes helped to achieve a system with a lower manufacturing cost and better acceptance, while considering the user in the development cycle.

INDEX TERMS Assistive technology, electromechanical devices, grasping, manual dexterity, rehabilitation robotics, research and development, user interfaces.

I. INTRODUCTION

Assistive robotics aims to improve the quality of life of individuals with severe or degenerative disabilities, motor or cognitive limitations (such as the severely disabled and elderly), or to substitute a lost function [1]–[3]. Currently, in Spain and the rest of the world there are millions of people who have some kind of functional disability [4]. Among the causes of this situation are spinal cord injuries, osteoarthritis, paralysis by stroke, etc.

This population requires help from third parties to perform the basic activities of daily living (DLA). According to their level of mobility, many of them are in a situation in which, while retaining much of the functionality of their upper limbs, they have difficulty to perform tasks that require some manual dexterity. Thereby, employing little tools used in DLA such as scissors, tweezers, nail clippers, etc. is difficult or even impossible for people with this kind of injury.

Related to this fact, a low cost assistive device has been designed with the aim to autonomously operate different tools that in a natural way require the grasping movement of the thumb and index fingers (i.e. a scissors). The operating mode consists of the substitution of natural grasping movement of fingers by an artificial movement generated by the electromechanical elements of the device. This artificial movement is transferred to a tool attached to the tip of the device, that is automatically actuated.

The device is made up of two basic parts: a main section and exchangeable tool heads. The main section houses, inside a case, the subsystems of the device: driving force, mechanical transmission, electronics, battery (in some models), and a touch-screen. The different exchangeable tool heads can be attached to this main section.

In this paper, both the hardware development and the software functionality of the assistive device are described. The remainder of this paper is organized as follows: Section II provides a brief overview of the initial design and a description of the device components. Section III describes the principle to generate a controlled linear movement on the device tip. The design process of the mechanical solution is also presented. Besides, the tool-oriented control designed to increase the device usability is detailed. Section IV summarizes the results of a pilot study of usability and manufacturing costs. The device features grouped by utility, ergonomy, use mode and control options, were assessed considering the participants' opinions. Based on the users' experience, a later improvement in the most control option was performed and subsequently tested in a second stage of trials. Then, the device performance in second trial and the contribution of the assistive device to improve the user autonomy in the DLA performing are studied. In addition, a review of original design specifications considering the influence of the individual device components on the global device functionality in order to reduce the manufacturing cost is included. Section V discusses the obtained results and the device performance in pilot trials. Finally, concluding remarks are presented in section VI.

A. RELATED WORK

The grasping and control of everyday tools is one of the main problems faced by the users to whom this device is addressed. Although there are solutions that will facilitate the grasping of daily utensils [5]–[8], which are only adaptations, the lack of control in the movements is a problem that still remains. This issue represents an important barrier to personal autonomy.

In a different way, several solutions based on wearable systems to assist the fingers movements are proposed [9]. In a study by Goutam and Aw [10] a cable drive and spring mechanism is used to provide an assistive downward force for the middle phalanx of the finger while the user grips an object. The cable tension simulates the functionality of a tendon. For the return action, the spring is used to transfer the linear actuator force. The prototype is implemented on a glove. Another system based on cable drive and linear actuators is presented in [11]. This device supports the movement of the thumb and forefinger. A complete hand exoskeleton is addressed in the Baker *et al.* study [12]. In this case, several aluminum bands are incorporated into a tight-fitting glove. The mechanical exoskeleton will be actuated using braided polymer cables attached to three linear actuators.

The previous systems addressed the lack of movement control, however they are research projects rather than operational devices. As an advantage over the use of a hand exoskeleton, our device presents a less intrusive solution, since the user is only required to grasp it in the same way as holding a smartphone.

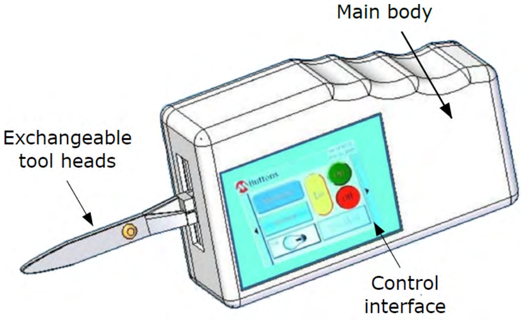


FIGURE 1. The assistive device's main subsystems according to the initial specifications.

II. METHODOLOGY

The portable assistive device has been designed to automatically generate opening and closing movements at the tip. It is aimed to assist people, who lack the manual dexterity required to use everyday tools such as scissors, nail clippers, or tweezers. This device can restore the lost ability by the user. The original idea consists of three basic elements: a main body, exchangeable tool heads and control interfaces. These elements are described as follows (see Fig. 1):

a) *Main Body:* This hosts the actuator, transmission, control interface, battery, and charger circuits (in the corresponding model). Also, it allows the user to connect the tool heads by means of special anchor docks and it moves them in linear guide. The external shape of the body was designed to be ergonomic and functional.

b) *Exchangeable tool heads:* Due to the diverse array of attachable tool heads the tip, and therefore the functionality of the device, changes from scissor tool, to small gripper, to tweezers or to whatever small tool is needed. They are all adapted to be mounted on the device. In this way, the same aid could develop a huge variety of tasks that require fine grasping abilities.

c) *Control Interface:* By default, the device is commanded by an embedded touch panel interface, which presents a menu of choices related to the attached tool head. For example, first the user chooses the type of tool connected depending on the task they want to perform, and then the touch-screen presents the right options to perform automatic pre-programmed movements in a suitable way for such tool.

A pilot study to investigate the impressions of individuals using our device in some common activities was conducted at two healthcare facilities. The first trial was carried out at Asociación de Parapléjicos y Personas con Gran Discapacidad Física de la Comunidad de Madrid (ASPAYM-MADRID) where individuals with different levels of spinal cord injury (SCI) participated. The second trial was conducted at Laboratorio de Análisis del Movimiento, Biomecánica, Ergonomía y Control Motor (LAMBECOM) where other individuals participated. Their physical conditions and the inclusion criteria will be detailed in the results section.

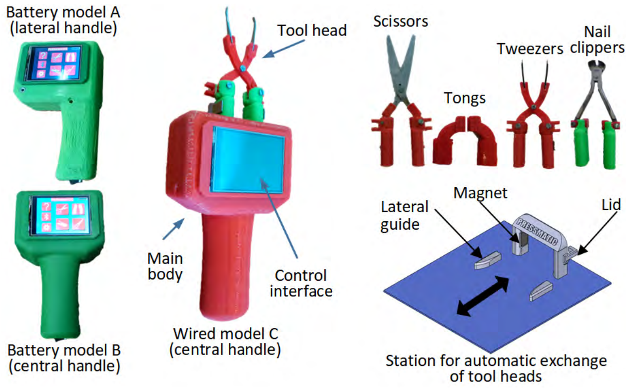


FIGURE 2. The assistive device's system with complete tool heads set and station for automatic exchange of tool heads.

III. A QUICK REVIEW OF THE MAIN DESIGN DECISIONS

From the design and specifications defined in [13] and [14], three assistive prototypes which had some morphological differences, but kept the same functionality, were developed (see Fig. 2 left). Models A and B are battery powered and their handle is placed either laterally or in the center, respectively. Model C is mains-powered and it has a central handle. Moreover, there are four tool heads as accessories: scissors, tongs, tweezers, and nail clippers (see Fig. 2 upper right corner). An automated system for exchanging tools (see Fig. 2 lower right corner) has been implemented to facilitate the use of them.

A. MECHANICAL FUNCTIONALITY

On the one hand, one of the main initial design decisions was to achieve a parallel movement for the clamping of the tools attached to the device. The device must be able to imitate the thumb and index finger movement. This type of movement keeps the relative distance between the tools' tips and the object to be manipulated. For example, for the nail clippers, the user only needs to place the device at the initial stage. The device then keeps the relative position of the nail clipper cutting edge with respect to the user's nail tip. In the case of using the scissors, this parallel movement in the attached blades makes it easier to cut due to device maintaining the initial cutting point position. However, other tools require of controlling the percentage of opening or closing of the tip's path. This is the case of both the tweezers and tongs tool heads.

On the other hand, the multi tool approach requires the design of a system to change the tools in an easy way. The user must be able to attach and remove the tools autonomously, moreover the fixation mechanism (anchor dock) has to be passive but strong enough to be functional and avoid undesired detach.

1) PRELIMINARY MODELS

Since the motion of the device tip must be linear, the first option was the use of a solenoid actuator. However, this kind of mechanism is a single-acting device. This option was discarded since the opening or closing movements should be as controllable as possible, allowing to vary the motion speed of the tool heads. Also, because the solenoid stroke is limited.

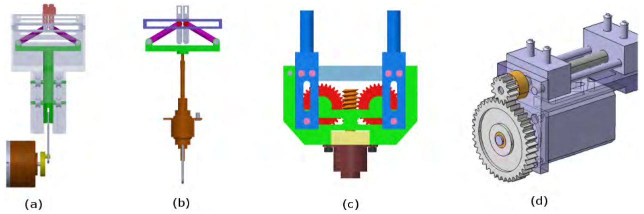


FIGURE 3. Detail of the development process of the end-effector system: a) Crank-based, b) Linear motor based, c) Endless screw and gears, and d) Bidirectional thread worm screw.

Several designs were evaluated by means of sketches and preliminary models based on a stepper motor. Among them, a crank-based system (see Fig. 3-a), a system that uses a linear motor as an actuator (see Fig. 3-b), an endless screw with side gear transmission (see Fig. 3-c), and a gear transmission with a bidirectional thread worm screw (Fig. 3-d) were considered. All the alternatives require leading guides for the terminals anchor docks to obtain a linear sliding motion on the device tip. The parallel translational movement desired is achieved in all cases, but with certain disadvantages.

The crank-based system (Fig. 3-a) requires more leading guides than the other models, and this causes jams during movement. This design was also larger. The system based on a linear motor (Fig. 3-b) was discarded because it cannot keep position without the motor being powered. This would imply a higher energy consumption (a shorter autonomy time of the device) because it cannot maintain position mechanically. Although the endless screw and side gear transmission design (Fig. 3-c) could maintain position mechanically, interlocking of moving parts occurred due to the necessary support points which were included to achieve linear movement. Thus, the gear transmission with a bidirectional thread worm screw system (Fig. 3-d) was selected to be implemented in the final prototype, since it is the smaller design and it only uses two leading guides to displace the anchor docks.

2) FINAL MECHANICAL DESIGN AND TOOLS' ATTACHMENT SYSTEM

The mechanical solution chosen to achieve the parallel motion on the tip is shown in detail in Fig. 4-a. Linear displacement (v_d) is obtained by means of the rotary motion of a stepper motor (ω_m) and an intermediary conversion mechanism based on gears and a worm screw (ω_{ws}). A half of the worm screw shaft has a right-hand thread, while the other half has a left-hand thread. This configuration obtains a bidirectional linear movement of the anchor docks.

Also, grippers and similar tool terminals, transmit force perpendicular to the contact surface, while keeping the angle between the contact forces and anchor docks null in the direction of linear movement [15]. Friction estimation is quite

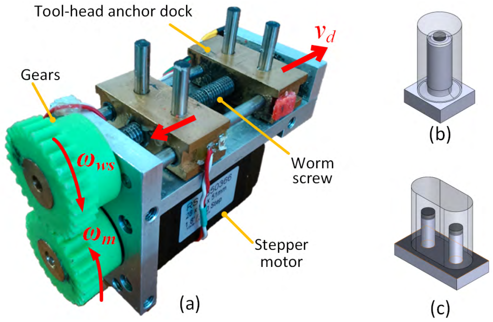


FIGURE 4. a) Detail of the final mechanical design used, b) First anchoring system, and c) Final system for attaching the tool heads.

complex; therefore, the actuator is oversized. A compression test of a spring was performed to estimate the grip force of the device. The displaced distance in the spring is multiplied by the spring constant to obtain the force. A limit in the current has been implement as a safety measure to prevent unintentional pinching. As result, the maximum grip force is close to 40 N.

Regarding the anchoring system, a stable connection is essential for the proper performance of the task intended for the tool. The design must be simple to allow an easy attach and detach of the tool head. The first design was based on cylindrical anchors tips with a magnetic material on the anchor tip as showed in Fig. 4-b. This magnetic knob retains the insertion of the tool head, but has the disadvantage that allows rotation of the tool. In Fig. 4-c the final solution duplicates the dock tips. Therefore, the rotation of the tool head is constrained. Notice that the magnetic knobs are also present in this final design.

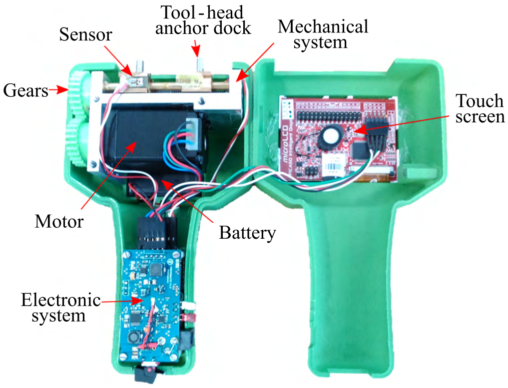


FIGURE 5. Distribution of components in the prototype model B (battery).

The placement of the mechanical transmission and the rest of components within the prototype is shown in Fig. 5.

B. TOOL-ORIENTED CONTROL

As was described in the previous section, a linear movement is obtained from a rotatory movement. Thus, controlling the motor spin translates into the control of the linear motion in the device tip. An Arduino compatible microprocessor ATmega2560 was chosen to program the motion control system. A motor driver Pololu A4988 is used to supply power to the stepper motor. The control of the linear travel axis is done by means of limit switches. A tool-oriented functionality has been implemented to control the device (see Fig. 6). That is, the user chooses the type of tool head connected depending on the task to perform, and then the device generates automatic pre-programmed movements in a suitable way for such a tool head. No automated tool identification has been implemented to keep the complexity of the system low.

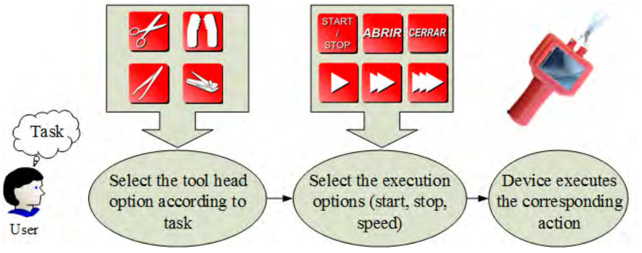


FIGURE 6. Tool-oriented control approach to control the device.

According to the tool heads chosen, three operational modes were implemented: continuous mode for the scissor tool head, simple mode for the nail clipper tool head, and grip mode for both the tweezers and the tongs tool head. The flowchart for the tool-oriented operating modes is shown in Fig. 7. Since the functionality is the same, both the tweezers and the tongs tool heads share the same operation mode.

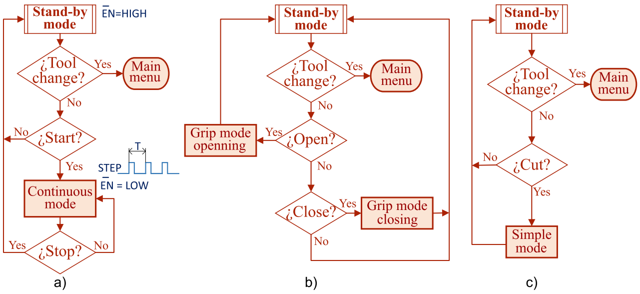


FIGURE 7. Flow-chart for the tool-oriented control modes. a) Continuous mode, b) Grip mode, and c) Simple mode.

1) CONTINUOUS MODE

This mode has been programmed for the scissors tool head to perform full opening and closing cycles indefinitely. The user must signal when to run and to stop the task execution. This operation mode (Fig. 7-a) begins with an idle state in which motor stepping is disabled (EN = '1'), waiting for a tool head exchange or the signal to begin the cutting process. Upon activation of such a signal, Continuous mode is entered, motor stepping is activated (EN = '0'), and a pulse wave with constant period is generated. While this mode is on, the device continuously performs complete opening and closing movements. Micro switches are used to detect the limit of the travel either on opening or closing mode. Their output is connected to two interrupts of the microcontroller that toggle the motor spin direction. When the user activates the signal to stop the cutting process, idle state is restored.

2) GRIP MODE

This mode is programmed to perform small opening or closing motions of the tool heads on user command. To achieve this functionality (Fig. 7-b), two control signals are required for opening and closing motions, respectively. The device is programmed to generate motion (open/close) while the corresponding control signals are activated to allow the user to hold full control over the motions. When there is no signal activation, the device keep position. If either opening or closing travel limit is reached, the motor will stay still until the complementary signal is activated. This is accomplished through the limit switches.

3) SIMPLE MODE

This is used for the nail clipper tool head and executes a full opening and closing cycle, equivalent to a single nail cut. The user would carry out another full cycle when ready. In this mode (Fig. 7-c), the opening motion is limited to one-half of the complete travel, enough to fit the nail in the tool. To maximize the force exerted, velocity change options are not allowed in this mode and the velocity itself is limited to the lowest value.

C. CONTROL CHANNELS

The control interface, intended for commanding the device, must achieve the accessibility and ease-of-use goals. To meet these requirements and reach the highest number of users, two communication channels have been developed: a touch-screen embedded on the device and a smartphone app.

1) EMBEDDED TOUCH-SCREEN

A touch-screen is integrated in the main body, and it displays the graphical interface implemented. The resistive screen uLCD-28PTU was selected due to its 2.8-inch size, suitability for our application, a simple graphic development environment, and serial port communications. A capacitive screen is usually a better choice in terms of touch sensitivity; however, a lower cost resistive screen was preferred to validate this prototype and assess the utility of an integrated screen. Several tool options are visually presented to the user through the touch-screen. To improve intuitiveness, tool-specific pictograms are used. Fig. 8 depicts a flowchart of functionality. Fig. 9 depicts the initial graphical interface design. Web accessibility criteria were considered in the design of the interface to improve icon visibility and make their function easily recognizable.

2) SMARTPHONE APP

The app is for Android OS and can be linked to our prototype via Bluetooth. The graphical design implemented in the touch-screen was preserved in the development of the first mobile app. That is, the same pictograms have been kept, as well as the navigation menus, colors and, primarily, an identical functionality. Moreover, all accessibility criteria from [5] and [16] have been included, too. Fig. 10 shows the menus implemented in the mobile app, which correspond to their counterparts developed for the touch-screen.

To link the smartphone with our device, its onboard electronics includes a low-cost HC-05 Bluetooth module. Predefined commands issued by a tap or selection actions are sent from the mobile app. This Arduino compatible Bluetooth module receives these commands and sends them through a serial port to the microcontroller, which executes the appropriate task. This smartphone based graphical interface presents certain advantages over the integrated

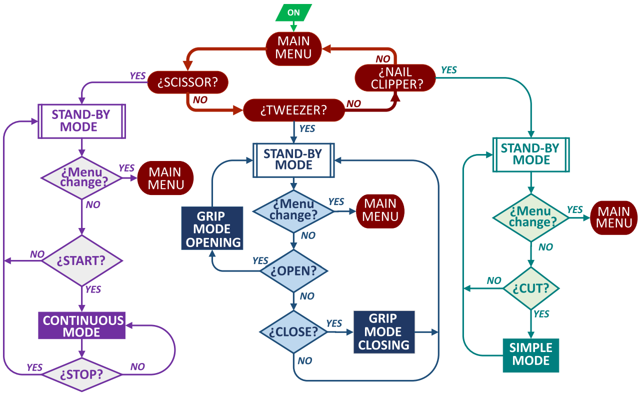


FIGURE 8. Flowchart of the menu window based touch-screen to control the device.

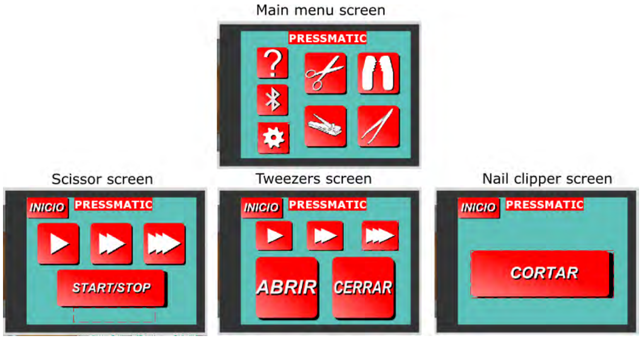
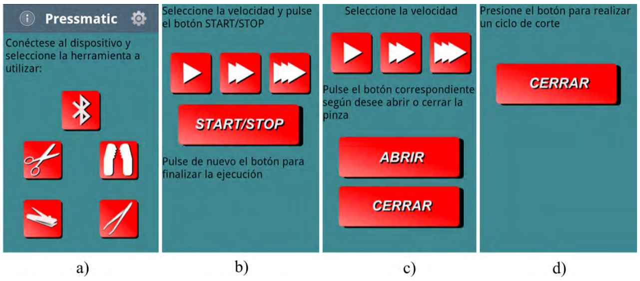


FIGURE 9. Graphic design of the menu window interface in the touch-screen.


Pressmatic

Conéctese al dispositivo y seleccione la herramienta a utilizar:

Seleccione la velocidad y pulse el botón START/STOP

START/STOP

Pulse de nuevo el botón para finalizar la ejecución

Seleccione la velocidad

Pulse el botón correspondiente según desee abrir o cerrar la pinza

ABRIR

CERRAR

Presione el botón para realizar un ciclo de corte

CERRAR

a) b) c) d)

FIGURE 10. Navigation menus in Android app: a) main screen, b) scissors screen, c) pincers screen, and d) nail clipper screen. Note that commands for open (abrir) and close (cerrar) are showed in Spanish.

touch-screen. Both can run simultaneously without interfering with each other, and any change or action applied in one interface will be reflected in the other. Therefore, users may control the device via the mobile app acting as a remote viewer. Also, the end-user is more familiarized with the smartphone device the app will be installed on, thus enabling a smooth and comfortable usage. Additionally, the smartphone's capacitive display greatly improves the touch sensitivity of the integrated resistive screen and makes it easier to use.

IV. PILOT STUDY OF USABILITY AND MANUFACTURING COSTS

A pilot study to investigate the impressions of individuals using the device in some common activities was conducted at two healthcare facilities [17]. A total of nine subjects, with both restricted and manual dexterity problems, were selected by medical professionals to compose the groups. Five individuals who have SCI between level C5 and C6 were selected to compose the Group 1. Four individuals were part of Group 2, three of them had hemiparesis, in two cases caused by a hemorrhagic cerebrovascular accident (CVA) and the other one in the aftermath of brain tumor. The fourth subject had akinetic-rigid syndrome caused by neurodegenerative Parkinson's disease (PD). All participants were eligible in accordance with the following inclusion criteria: a) Affectation of the upper extremity; b) Grabbing ability; c) Spasticity according Modified Ashworth Scale $\leqslant 2$; and d) Ability to understand Mini-mental test instructions $\geqslant 24$.

Demographic data and the expertise level on controlling a smartphone of the participating groups are presented in Table 1. The gender is: (F) for female and (M) for male. The previous experience of the participants regarding the use of smartphones, considering their opinions, was defined as: Beginner (B), Intermediate (I), or Advanced (A).

TABLE 1. **Demographics of participants in the study.**

		Pathology	Age	Gender	*Exp.
Group 1	P1	SCI on C6 level (complete)	35	M	A
	P2	SCI on C5 level (complete)	30	M	A
	P3	SCI on C6 level (complete)	35	M	A
	P4	SCI on C5/C6 level (complete)	40	M	I
	P5	SCI on C6 level (incomplete)	30	M	A
Group 2	P6	Hemiparesis by CVA	54	F	A
	P7	Hemiparesis by CVA	23	M	A
	P8	Hemiparesis by CVA	55	M	A
	P9	Akinetic-rigid syndrome by PD	58	F	I

*Exp.: Level of expertise on using a smartphone

A. USABILITY TEST RESULTS

Several tasks were proposed to perform, such as picking up small objects, cutting a sheet of paper or exchanging tool heads. All tasks were performed using our device and an appropriated tool head. The device features and its control interfaces were individually evaluated by each user, who expressed their opinions via a range of satisfaction scores, from -2 (strongly disagree) to $+2$ (strongly agree). Regarding the number of users for a proper usability assessment, five is a proper number for usability testing, according to [18] and [19]. Considering these criteria, and since one subject was unable to attend the second trial, the results have been processed as a single group.

TABLE 2. **First results for the usability questionnaires.**

	Mean	Mode
Utility		
1) Could it gives more independence to you in DLA?	1.33	1
2) Useful for people with your same injury?	0.78	1
3) Would you buy it if you could?	0.78	1
Ergonomy		
4) Is it easy to handle?	-0.44	-1
5) Size and weight adequate?	-1.56	-2
6) Is the device shape user friendly?	-0.56	-2
Use mode		
7) Scissors task completed?	0.56	1
8) Tweezers task completed?	1.11	1
9) Tool heads easily exchanged?	0.56	1
Control options		
10) Touch screen easily used?	0.56	-1
11) Smartphone App easily used?	1.67	2
12) Previous options easily used?	1.33	1

Questions were classified based on four categories and the results are presented in Table 2. The best results were obtained in both Utility and Control options categories. Thus, device was found easy to control by the individuals and that it could be useful in their DLA. Also, a favorable result is achieved for the Use Mode category, and it has an added value, when the fact that all participants could perform the proposed tasks is considered. The Ergonomy category has obtained the worst results. All the participants agreed that the current device weight decreases its usability. The current device weight is 620 grams in A and B models, those that use batteries, though not optimal, allowed proper manipulation of the device. In the case of the wired model C, the weight is 595 grams.

B. IMPROVING THE MOBILE APP BASED ON USER EXPERIENCE

The target was to improve the usability of the mobile app that controls the device. An important requirement is to maintain the functionality that currently exists so that the back of the current development is reusable and only involves changes in the front layer. For this, a specific redesign process based on Ries's Lean Method [20] was followed, and adapted to the characteristics of this project and its starting point. Throughout the process of redesigning the remote-control app of the device, the characteristics of the target users and their satisfaction have been taken into account. The deliverable to be evaluated again, was a navigable model, formed by the final screens and specifications, that will allow any developer to implement the app. Alongside the design improvements, the accessibility and the use mode were improved too. The graphic line of the new version of the mobile application was developed to convey the following values: accessibility, closeness and simplicity.

The user interaction with the control app has been redesigned for simplicity, considering the ability to store previous interactions of the user, choosing predefined speeds and commonly used tools. The colors used for the icons and screens, was also revised, according to these principles. The choice of main colors was somewhat more complex since it was intended to be accessible to all people with some deficiency of color vision (color blindness). The spectrum of colors according to the various deficiencies of the dichromatic colorblind (Protanopia, deuteranopia, and tritanopia) was reduced.

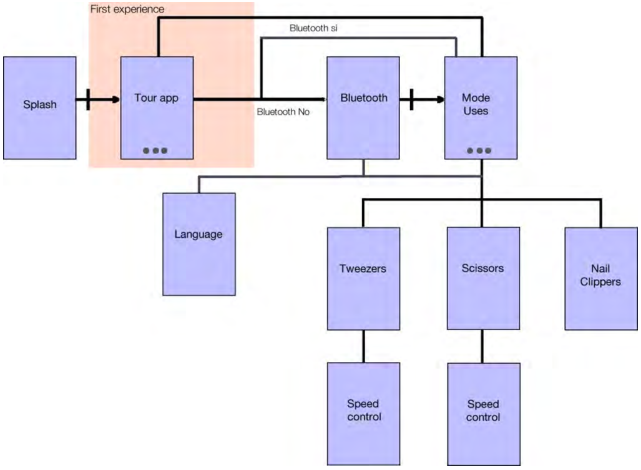
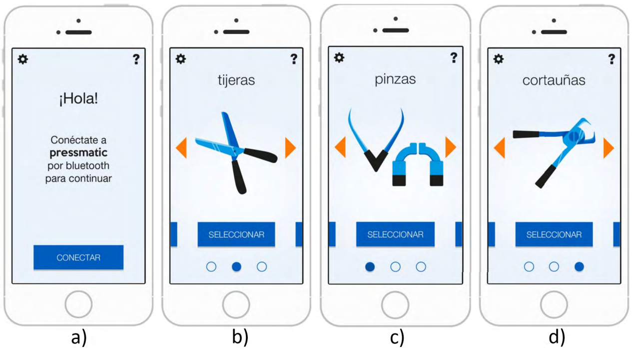


FIGURE 11. New flowchart of the menu window based touch-screen to control the device.

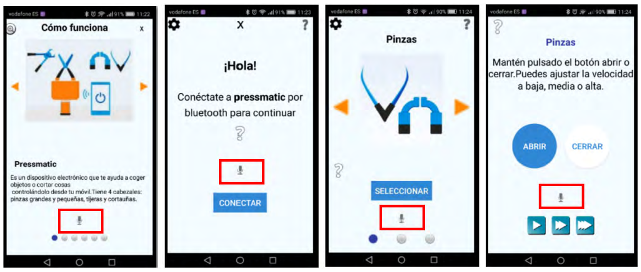
Although the device has four heads: large tweezers, small tweezers, scissors, and nail clippers; The operating modes and the control of the large and small clamps are the same, and so they have been grouped into a single option. From the mode selection screen, the user can select the usage head. Fig. 11 illustrates the flowchart of the new app.


¡Hola!

Conéctate a **pressmatic** por bluetooth para continuar

FIGURE 12. Navigation menus in the new Android app: a) main screen, b) scissors screen, c) pincers screen, and d) nail clipper screen. Note that only the name of the tools and selection buttons are shown in Spanish.

To guarantee the contrast between the colors we chose to use: light tones for the background; black and blue for the main elements; and orange tones for minimalist details. The new graphical design is shown in Fig. 12. The user tests were done using the "Thinking Aloud" technique. It consists of asking the user to do a task and the participant is asked to verbalize everything he or she is thinking and explain why he performs the actions he performs. After some interactions and verification with real users of ASPAYM-MADRID veterans in the handle of the device, this design was implemented again in both iOS and Android systems, including HTML5. Considering the participants' suggestions and based on the user experience approach, the design and the usability of the control app was improved. Fig. 13 presents some help menus that presents instructions to use each tool head, according to the tool-oriented approach.


Cómo funciona

Pressmatic

Es un dispositivo electrónico que te ayuda a coger objetos o cortar cosas controlándolo desde tu móvil.Tiene 4 cabezales: pinzas grandes y pequeñas, tijeras y cortauñas.

¡Hola!

Conéctate a **pressmatic** por bluetooth para continuar

Pinzas

Mantén pulsado el botón abrir o cerrar.Puedes ajustar la velocidad a baja, media o alta.

FIGURE 13. Tool-oriented approach to control the device in the new iOS app for the pincers tool head. Note that text is shown in Spanish.

Regarding how the user interacts with the App, the trials with the first app version showed that the participants were able to navigate through the App menus and to activate the buttons without difficulty. The capacitive screen of the smartphone contributes to this fact.

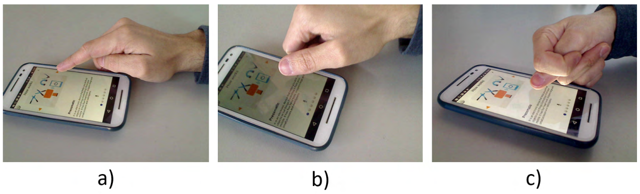


FIGURE 14. Detail of how a user interact with the device app in the new iOS app. Touching the tactile screen with: a) the index finger, b) the thumb, and c) the thumb supported by index finger.

Different ways of how the participants touched the screen were identified. That is, the participants used to touch the screen in several ways such as with the index finger, the thumb finger, the thumb supported by the index finger, or the fist (see Fig. 14). Moreover, a voice control based on the Google talk voice recognition was included in the new version.

Finally, some customization options (language change, text or buttons resizing) were added to increase the App's accessibility.

C. STUDY OF PERFORMANCE

A new trial was carried out in February of 2018 at the same healthcare facilities and with the same participants. This study was focused on testing the new app which was redesigned based on the users' experience. Also, to evaluate the success rate of the device in task performing.

For that purpose, a three-level scale was designed, similar in structure and detail to the feeding and dressing sections of

TABLE 3. Level of autonomy to perform a task and results for the usability questionnaires for each participant. The levels of autonomy were defined as: Independent (I), Needs Help (NH), and Dependent (D).

	Group 1					Group 2				Mean	Mode
	P1	P2	P3	P4	P5	P6	P7	P8	P9		
Autonomy level on											
Using the smartphone	I	I	I	I	I	I	I	I	I	n/a	n/a
Paper-cutting	NH	D	D	D	D	NH	I	NH	NH	n/a	n/a
Nail-cutting	D	D	D	D	D	NH	NH	NH	NH	n/a	n/a
Small objects grabbing	NH	D	NH	NH	NH	NH	I	NH	I	n/a	n/a
Task 1: paper-cutting											
Scissor task completed?	1	1	1	2	2	2	2	2	2	1,67	2
Easy to perform?	1	1	1	1	2	1	2	2	1	1,33	1
Did you use the touch screen?	0	-1	-2	0	-1	0	0	0	0	-0,44	0
Did you use the app?	2	2	1	2	2	2	1	2	1	1,67	2
Was the voice control useful?	1	2	2	2	1	2	1	1	-1	1,22	1
Task 2: pick-up small objects											
Pick&place task completed?	2	1	2	1	2	2	2	2	2	1,78	2
Easy to perform?	1	1	2	1	2	2	1	1	2	1,44	1
Did you use the touch screen?	0	0	0	-1	0	0	0	0	-1	-0,22	0
Did you use the app?	1	2	1	1	1	1	2	2	1	1,33	1
Was the voice control useful?	0	1	1	1	1	2	1	1	0	0,89	1
Task 3: finger nail-cutting											
Nail-cutting task completed?	-1	-2	-1	-2	0	-1	0	1	-2	-0,89	-1
Easy to perform?	-1	0	-1	-1	1	-1	0	-1	-2	-0,67	-1
Did you use the touch screen?	0	0	0	0	-1	0	0	0	-1	-0,22	0
Did you use the app?	1	2	2	2	2	2	2	2	1	1,78	2
Was the voice control useful?	1	1	2	2	2	1	1	2	1	1,44	1
Task 4: tool heads exchange											
Tool heads exchange task completed?	2	2	1	2	2	1	1	2	1	1,56	2
Is this function useful?	1	2	2	2	1	0	0	0	0	0,89	0
Did you use the touch screen?	-1	0	0	0	-1	0	0	0	0	-0,22	0
Did you use the app?	1	1	2	2	1	1	2	2	1	1,44	1
Assessment of app functionality											
Has the app been intuitive to use?	2	2	2	2	2	2	1	1	1	1,67	2
Have you been able to use it without help?	2	1	1	1	2	2	2	2	1	1,56	2
Has the graphic design been adequate?	2	2	1	2	1	1	2	2	1	1,56	2
Is the icons/buttons size appropriate?	2	1	2	1	2	2	2	1	1	1,56	2
Is the voice control useful?	1	2	1	2	2	1	2	2	1	1,56	2
In general, is the app functionality adequate?	2	2	2	2	2	2	2	2	1	1,89	2

the Barthel ADL Index [21]. The design evaluates the degree of autonomy of the participants to perform the tasks proposed in the pilot trial without the device. The levels of autonomy were defined as: Independent (I), Needs Help (NH), and Dependent (D). The responses of the participants are summarized in Table 3, including the results of the tasks being performed. On this basis, the contribution of the assistive device to improve the user independence in the DLA performing can be discussed. Note that for this test, the participants have used the proposed device for the second time.

1) TASKS DESCRIPTION

Four tasks were proposed to be performed by the participants, using the assistive device. Three of them using different tool heads, and the last one to evaluate the automated system for exchanging tool heads. The first proposed task was to cut, using the assistive device with the scissors tool head, several simple geometric figures (circle, triangle or square) printed on a sheet. As second task and using either the tweezers or nippers tool heads, it was proposed to pick up a series of small objects within a box, and then take them out. In this way, both the comfort to manipulate the device and its ease to perform the tasks were assessed. The third proposed task was fingernail cutting by using the nail clippers tool. Finally, the fourth task consisted of tool heads exchange by using the station for automatic exchange.

In the first three tasks, the participants were encouraged to place the tool heads on the device by themselves. If they failed, an evaluator placed the tool heads for them. Regarding the control of the device, the individuals could choose between the touch screen or the new app. The participants were free to use the voice control option when they considered it appropriate.

2) DEVELOPMENT OF THE TASKS AND RESULTS

The results of the questionnaires, to gather the opinion of participants about the development of the tasks, are summarized in Table 3. The participants' opinions were expressed via a range of satisfaction from -2 (strongly disagree) to $+2$ (strongly agree). Some pictures of participants performing the tasks during the trials are shown in Fig 15. At the beginning of the trials, the App was available for the participants to download. They installed the new app in their own smartphones.

In the case of the paper-cutting task, the results were favorable (1.67). All the participants were able to complete the proposed task in different periods of time, according to their motor limitation and dexterity. Note that the participants

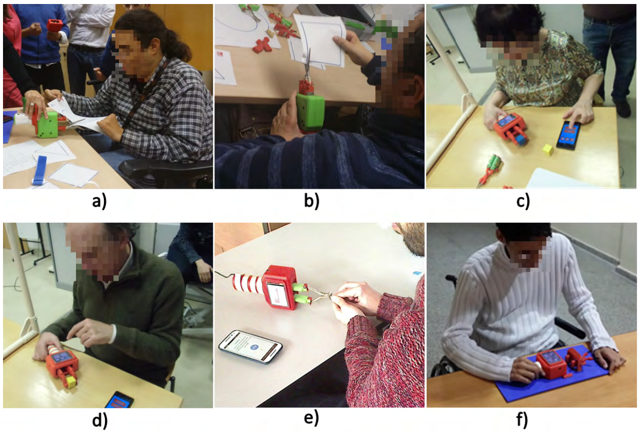


FIGURE 15. Participants performing the tasks proposed. a) P2 in paper-cutting task, b) P1 in paper-cutting task, c) P6 grabbing small object, d) P8 grabbing small object, e) P7 in nail-cutting task, and f) P5 in tool head exchange task.

of Group 1 (quadriparesis), having both arms affected, took more time to complete the tasks than the participants of Group 2 (hemiparesis). It must be highlighted that, the participants from Group 1 have the capacity to adapt their motor limitations to the needs of the task, using the device in the best possible way. For example, Fig. 15-a shows how an user placed the device on the table with the scissor tool head pointing to him. By using the app, the user activated the continuous mode that automatically executes opening and closing cycles. The user is able to hold the paper with both hands and he only has to guide the paper while the scissor blades are automatically cutting. As it is shown in Fig. 15-b, another user leaned the device to the table to cut the paper, safely holding the device with one hand and with the other one holding the paper.

Task 2, picking up small objects, was successfully completed by all participants (1.78). Most of the participants performed the tasks only controlling the device by the smartphone app. Participants of Group 2 were those that more easily used the App, since they have more strength in their arms. The voice control was more useful to Group 1, being able to complete the task by speaking the open and close commands. Due to the way the Grip mode works, that is, a limited displacement of the tool head, the users are required to repeat the voice commands as many times as needed.

The worst results were obtained for the nail-cutting task (−0.89), since only two participants were able to complete the task. This results can be analyzed from two point of view: the use mode and the device capacity. On the one hand, regarding the use mode the participants found that the better way to use the nail-clippers tool head was leaving the device on the table with the tool head pointing to the user (see Fig. 15-e). This method allows the user to be hands free. However, the task could not be completed in all the trials due to the fact the motor power was not enough. In addition, the 3D printed pieces of the tool head suffered undesirable flexion, increasing the losses in power transmission.

In the case of task 4, the station for automatic tool head exchange was positively accepted by all participants, and it was strongly appreciated by Group 1. The tool head exchange was easy for Group 2. This fact is understandable because Group 1 participants' have both arms affected, contrary to Group 2 that still have functionality of one arm.

Regarding the assessment of the new developed app, in general the user experience when using the new app was very satisfactory (1.89). Thus, the new app was useful to perform the tasks designed for this pilot trial. The intuitive graphical design (1.67) and the ease for menu navigation (1.56) were also highlighted. The options to customize the graphical interface (1.56) were appropriate. Besides, the voice control option was reported as useful and it increases the accessibility of the assistive device.

D. REVIEW OF ORIGINAL DESIGN SPECIFICATIONS

The baseline design requirements were in-depth reviewed in [17], according to the impressions and user experience. On this basis, the device components were grouped by the essential ones to maintain the device functionality and the other ones that can be considered optional. A cost point of view analysis was added to the previously mentioned classification (see Table 4), in order to identify the impact of the review of initial requirements of design in the final cost of the device.

A system made up of a main body and exchangeable tool heads is strongly accepted and the multi-tool approach is highlighted by participants.

The tool head set is positively valued but an extension with more tools is requested. The device portability of both A and B models is well appreciated, but the wired condition of model C does not decrease its usability. The central handle models were preferred. With respect to device control, the option of control by cell phone was highlighted to the detriment of control by touch-screen. The idea of controlling the device from their own smartphone increases the device usability, since they are familiar with their mobile phone. Considering the users experience, the embedded touch-screen is not an essential element.

Regarding device weight, all participants ask for its reduction. For that purpose, to remove the touch-screen is a good option, based on the previously mentioned user impressions by using the app. This design modification, involves a weight decrease of 6.5% and a reduction of 8% in the prototype cost. Besides, the mechanical solution to generate a linear movement uses 68.4% of the prototype weight, therefore, an important issue in future developments is improving the current mechanical system. This consideration could induce a remarkable decrease in manufacturing costs since both the motor and the mechanical system are two of the most expensive elements among the essential ones.

V. DISCUSSION

As was shown in [13] and [14], the target population to use our assistive device were people with SCI between

TABLE 4. Device's components and its influence on functionality and manufacturing costs.

	Component	Description	Weight [g]	Used on all prototypes	Utility for the users	Influence on functionality	Cost per prototype [€]
Essential	Mechanical	Transmission system in aluminium 7075	22	Yes	-	H	366.66
	PCB	FR4 two layers	11	Yes	-	H	141.24
	Motor	RS 535-0366 stepper motor	200	Yes	-	H	97.78
	Electronics	Resistors, Capacitors, etc)	12	Yes	-	H	61.79
	Tool heads	3D printing in ABS	30	Yes	H	H	30.00
	Case C	SLS technology printing (central handle)	103	No	H	H	122.00
	Motor driver	A4988 stepper motor carrier	2	Yes	-	H	6.50
	Bluetooth	HC-05 Bluetooth module	3	Yes	H	M-H	5.85
	App	App for smartphone	-	No	H	H	Free
							Subtotal 1 = 831.82 €.
Optional	Case A	3D printed in ABS (lateral handle)	101	Yes	L	M	20.00
	Case C	SLS technology printing (central handle)	103	No	M	M	122.00
	Soldering	SMD components soldering	-	No	-	-	122.00
	Touch-screen	uLCD-28PTU 2.8" LCD module w/ Touch	35	Yes	M	M	72.25
	Battery	DSK for Galaxy Note III	25	Yes	M	M	11.9
							Subtotal 2 = 348.15 €.

Influence on functionality could be: High (H), Medium (M) or Low (L)

C5 and C6 levels (Group 1). However, people with hand motor impairments caused by a neurological disease (Group 2) can also use the device, as it is described in this paper.

On the one hand, the contribution of the developed assistive device to the autonomy of participants in DLA performing can be analyzed from the conducted tests. The level of autonomy of participants to perform the proposed tasks in daily living was measured through questionnaires. First, all the participants declared they are self-reliance to use a smartphone. The expertise of each participant was summarized in Table 1. It can be seen, that all of them have an intermediate or advanced level. Thus, the management of the new app for controlling the assistive device could not be a barrier.

On this basis, the participants of Group 1 were dependent to perform task 1 without the device, while Group 2 needed help to accomplish it. By using the assistive device, all the participants were able to complete the paper-cutting task without help, giving them more autonomy. For the case of task 2, most of the participants told they needed help to grab small objects, while two individuals of Group 2 told they were able to handle little objects by themselves. Thus, it can be seen that the tweezers tool head was more valued for participants of Group 1, that are able to hold the device by mass flexion of fingers but they are not able to grab little objects that require fingers dissociation. Related to task 3, Group 1 expressed they were dependent for nail-cutting task, while Group 2 individuals need help to hold the nail-clippers with the affected arm.

On the other hand, it is not only important the assistance provided, but safety should also be considered. In the case of paper-cutting task, some users suggested to increase the cutting speed of the scissors blades. This fact highlights the users' impression of the reliability of our device, being appreciated as a non dangerous device. Note that engine speed for the scissors tool heads was reduced by software before the trials were conducted, with the aim of keeping the user safe while interacting with the device. If needed, this speed could be easily setup by software increasing the commutation speed of the steeper motor.

Knowledge of the user is as important as system functionality, since without the user's cooperation, functionality may be ineffective [22]. On this respect, after the last trial in February, it can be noted that the acceptance for the new app is good, both in the front end design and in its functionality. Due to their reduced manual dexterity, Group 1 have much more appreciated the improvements on the app usability with respect to the older app.

Also, note that the functionality of voice control was very valued for all the participants. Nevertheless, also it has been noticed that for task executing commanding by voice, some issues arise, that allow space for improvements. First, the usability of voice control could depend on the task to be performed, as for the case of paper-cutting that requires one command to start and another one to stop the cutting motion. For the case of grip mode, several voice commands will be required according to the size of the target object. Additionally, some failures in voice recognition processes were generated because of the noisy engine actuation, especially with the device leaning on the table. In these cases, the user had to repeat the voice commands on several occasions.

Regarding the ability of using smartphones in people with SCI, the Kim *et al.* study [23] shows that when the SCI patients use smartphones with the appropriate guiding devices, they are expected to access mobile cellular devices faster and with more satisfaction. However, users with SCI between C5 and C6 levels chose universal cuff with stylus or bare hands to interact with smartphone.

In our study, the participants from Group 1 were individuals with SCI on C5 and C6 levels. The trials show that they were able to use the smartphone with bare hands, but with different ways of touching the screen as it was previously described in Fig. 14. Besides, a variety of smartphone applications to assist individuals living with a SCI are currently available on the market [24]. This fact supports the use of an app for controlling the device presented in this paper.

VI. CONCLUSIONS

This paper presents a systematic approach to analyze and review an assistive device. For that purpose, the hardware development and functionality description of a novel assistive device were presented. Three functional prototypes with ergonomic differences were implemented. Several commonly used electronic devices, such as touch-screen, stepper motor, microcontroller, etc., were used to obtain a novel application. A tool-oriented control to increase the device usability was developed. The device functionalities and control channels and modes were analyzed by means of performing usability trials, and then it was discussed their contribution to the final cost of the prototype. Additionally, a two stages pilot study, focused on the design considerations and user experience, is presented.

It is highlighted that the proposed device covers a real need and its functionality is adequate according to the user experience in pilot trials. However, some considerations must be taken into account to improve the usability of the device, such as tool head set extension, weight reductions, and touch-screen removal. Besides, a new version of the App, that was more considerate of the user experience, was developed and tested. This version has been rebuilt, taking into account the principles of User Experience (UX) design to drastically improve its usability. Also, the new control app includes the Android speech recognition to control the device by voice commands. This fact increases the device usability.

Based on the user experience and the cost of the device's components, the original design specifications were evaluated. Thus, the device components were classified according to their influence on device functionality. It must be highlighted, that participants think that the embedded touch-screen could be removed, and the better way for controlling the device is through the App. This consideration could reduce size and weight of the device, as well as an 8% reduction in prototype cost.

This study has also developed a proper method to quickly capture the acceptance by target users of the proposed functionalities, such are intended to help them to recover their autonomy in DLAs. Besides, the required improvements to boost the user adherence to the device have been remarked. The results presented, and the evaluation by target users, further support the development of a newer and lighter device, to obtain an affordable system to assist people with reduced manual dexterity to improve their autonomy in DLA.

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