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Designing and Integrating Electronics for Bespoke Rehabilitation Experiences in Virtual Reality

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Abstract. Available virtual reality (VR) input devices, such as controllers enabling user interaction with the virtual environment, typically do not meet the requirements for rehabilitation. The therapeutic exercises used in the treatment of neurological disorders (e.g., stroke or musculoskeletal injuries) are mainly associated with rehabilitating the muscles of the arm, wrist, and fingers. Design requirements for devising a therapeutic interaction technique for VR rehabilitation training systems (RTSs) include sensing, identifying other input requirements, and setting exercise parameters using outputs. Therefore, dedicated electronics solutions are needed to meet the needs of bespoke rehabilitation experiences in VR. In this study, therapeutic interaction requirements were identified by exploring therapeutic exercises. The aim is to provide a dedicated electronics solution incorporating input and output systems developed for therapeutic purposes. We identify design requirements to be considered when designing and implementing electronics for rehabilitation training in VR. These cover power, connectivity, modularity, and operational and physical design requirements. The proposed electronics solution fulfills these requirements and is integrated into a bespoke controller for VR rehabilitation. Furthermore, in this article, we (1) provide a set of design principles for designing a therapeutic interaction technique for VR headsets; (2) describe the process involved in the design and integration of electronics for bespoke rehabilitation experiences; (3) demonstrate how the electronics meet the requirements of the prototyping development process; and (4) describe the design and working principles and integration of custom electronics in a bespoke controller for VR rehabilitation. The proposed electronics solution fulfills the requirements of bespoke controller designs and provides per-patient customized interactions. Moreover, the solution allows for adjustment of the level of the rehabilitation exercises using outputs and recording of the patient performance data, which can be utilized by therapists.

Keywords: virtual reality, VR input devices, electronics, rehabilitation, bespoke rehabilitation experience.

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1 INTRODUCTION

Patients with upper limb impairment, particularly following stroke, are severely impacted in their activities of daily living (ADL). A large portion of all stroke survivors are left with severe functional problems and show upper limb impairment, often on one side, several months later. Rehabilitation services for these types of dysfunctions aim at improving the activity limitations of patients with upper limb impairments.

Virtual reality (VR) provides controllable, safe environments that enable individual training and rehabilitation [1],[6-7],[16]. With the availability of a wide variety of cheap VR equipment, VR rehabilitation is gaining popularity and is being utilized to treat neurological problems.

The therapeutic exercises employed in the treatment of neurological illnesses, such as stroke or musculoskeletal injuries, are primarily concerned with repairing the arm, wrist, and finger muscles. In most cases, available off-the-shelf VR input devices, such as controllers that enable user interaction with the virtual world, do not meet rehabilitation standards for the treatment of such neurological illnesses.

2 RELATED WORKS

Various VR rehabilitation-focused systems have been developed in the recent decades [12],[15-16]. Such systems typically involve elaborate virtual environments (VEs), such as games and rehabilitation exercises, displays with different degrees of immersion, and interactive interfaces with the VE. With regard to the interactive interfaces and electronics used, the related studies can be classified in the following ways: (1) gesture-based, (2) feedback-focused (visual, audio, tactile), (3) robotic-based, and (4) handheld. Studies related to each method of interaction are discussed in the following sections.

2.1 Gesture-based Input Devices

Khademi et al. [12] explored the technology of device-free gesture-based interaction methods to rehabilitate patients with stroke using the modified game of Fruit Ninja and a Leap Motion controller. Their system includes a modified PC version of the Fruit Ninja game, which can be played using hand movements on a laptop with a Leap Motion controller. They also gamified the rehabilitation exercises to motivate the stroke patients. Their system was tested with 14 patients, at least 6 months post stroke, with different levels of disability. Apart from four participants, all other patients were able to play the game using their fingers.

2.2 Feedback-focused Input Devices

Reh@Task is a multipurpose VR scenario system for upper limb reaching and cognitive training. It allows for the customization of stimuli, training tasks, and training progression. The setup consists of a webcam, a display, and a handle with a tracking pattern. The user works on a table facing a monitor and moves the handle on the surface of the table with his/her arm. An augmented reality pattern-tracking software is used to capture upper limb reaching movements in 2D. The VR scenario adapts the task to individual users using a built-in calibration function, which normalizes the motor effort required in the task to the skill set of the user. The user's movements are then mapped onto the movements of a virtual arm in the VE [4].

2.3 Handheld Input Devices

Neil et al. [15] attempted to compare the Sony EyeToy camera, which is compatible with the PlayStation, to the Nintendo Wii in terms of (1) usability, (2) user experience, and (3) intensity of movements. The EyeToy uses video capture software to project the user's image onto a VE. The researchers strapped accelerometers around the participants' wrists to measure the intensity of activity movements and used a questionnaire to evaluate the participants' perceived satisfaction and enjoyment, as well as the usability of the system.

2.4 Robotic-based Input Devices

Robots and mechatronics also provide a convenient interface with VEs. These VEs have been recently applied to rehabilitation paradigms for stroke survivors. For example, Fischer et al. [5] investigated the impact of assisted motor training in a VE on hand function in stroke survivors with chronic upper extremity dysfunctions. The authors developed two assistive devices for finger digit extension using a novel cable orthosis (CO) and a pneumatic orthosis (PO). The CO consists of a simple prosthetics technology with five cables; each cable is attached to the tip of a digit on a glove. The PO comprises a nylon glove and a single air bladder chamber, which are sewn onto the palm side of the glove.

Apart from the classification of the studies based on interaction, Table 1 classifies relevant studies based on the type of system developed for the rehabilitation of the upper limb.

Rehabilitation system target	*Study*	*Display device*	*Input tracking*	*Output*	*Ref.*
Upper limb (hand)	Sampson et al. (2011)	Computer display	Webcam	-	[17]
	Lee et al. (2016)	Computer display	Webcam	-	[13]
	House et al. (2016)	Computer display	Webcam	-	[11]
Upper limb (in general)	Holden and Dyar (2002)	3D display and glasses	Sensors	-	[9]
	Hilton et al. 2011)	Touch screen	Webcam/sensors	-	[8]
	Broeren et al. (2016)	3D display and glasses	Haptic input device	Haptic	[2]
	Chiang et al. (2017)	Computer display	Haptic input device	Built-in calibration	[3]
	Faria et al. (2018)	Computer display	Webcam	-	[4]
Upper limb (forearm)	Holmes et al. (2016)	Head-mounted device	Sensors and hand-tracking device	Light & haptic	[10]
	Lupu et al. (2016)	Head-mounted device	Hand-tracking device	Haptic	[14]
	Wang et al. (2017)	Computer display	Hand-tracking device	-	[18]

Table 1: Studies on system development for rehabilitation of upper limb.

From the standpoint of design and integrated electronics, most of the systems described above use either computer vision-based solutions (such as Leap Motion controller or webcam) or handheld devices (such as gloves). Therefore, according to the literature review, it can be said that no study presented the electronic solution for a bespoke controller for upper limb rehabilitation using VR. Particularly, no study used a force-sensitive resistor (FSR) sensor for that purpose. Unlike the above studies, in this work, the need for therapeutic interactions was established by examining the therapeutic exercises. Therefore, this study delivers a specialized electronics solution that includes therapeutic input and output devices. The main objectives of this study are as follows:

- To provide a set of design principles for designing a therapeutic interaction technique by sensing muscle activity for VR headsets
- To describe the process involved in the design, manufacturing, and assembly of two different types of electronic circuit boards
- To demonstrate how the design iterations of the electronic circuit boards meet the requirements of the prototyping development process
- To describe the design and working principles of two different printed, electronic circuit boards

3 DESIGN PROCESS AND REQUIREMENTS

After reviewing the domain of interaction paradigms from the literature, a set of therapeutic movements and potential sensing mechanisms to capture these movements were highlighted in this section. The identification of therapeutic movements can be considered an essential task for electronic circuit design to determine the appropriate sensing mechanisms to capture these movements. However, immersive VEs also require the users to perform additional input tasks using a variety of input devices (e.g., buttons, triggers, and joysticks). Therefore, it is also important to identify the required additional input devices to define the electronics requirements for the bespoke controller. Hence, we defined design requirements and principles for designing a therapeutic interaction technique by sensing muscle activity for VR headsets.

3.1 Output Hardware Requirements

The hardware that presents the VEs to the user is called an output or display device. These output devices must be considered when designing and developing input devices as certain interaction techniques are more appropriate for particular displays. After reviewing the literature, we chose a tethered headset that acts as a display for another device such as a PC instead of a standalone device. Such platform offers wider possibilities of hardware and software development. Therefore, a tethered head-worn display device (or headset) was considered in this study. In particular, the SteamVR tethered VR hardware and software platform developed by Valve was chosen to develop the virtual rehabilitation platform (VR-HABIT). The VRHAB-IT platform is integrating the following the components (1) VR headset (e.g., Valve Index), (2) VR controller designed for the specific patient groups, (3) VR games providing interactive therapeutic environments to the patient groups, and (4) Software dashboard incorporating the user control interface showing aspects of gameplay and feedback. The platform includes a module allowing the users to select and start particular VR game, and a module to monitor and control the VR games.

3.2 Input Hardware Requirements

As mentioned above, choosing appropriate output devices is an essential component of designing and developing VEs, as they present the virtual scenes to the user. An equally important part of developing VR-HABIT is choosing an appropriate combination of input devices that allows the user to interact with the system. Like output devices, there are many different types of input devices to choose from when developing VR-HABIT, and some devices are more suitable for specific input tasks. The input devices can be characterized by the input type and frequency of data they aim to generate. Input systems data frequency can be either discrete, continuous, or a combination of the two. Input devices can also be described based on the types of sensors they use to capture data. For instance, active sensors require the user to physically manipulate the device to generate useful data to interact with the VEs. Input devices with active sensors can generate both discrete (e.g., buttons) and continuous data (e.g., trackpads). By adapting the designs of the commercial VR controllers, such as Oculus Touch and Vive controllers, this study only considers analog joysticks, buttons, and triggers, in addition to the active sensors, to capture therapeutic movements for the bespoke controller design.

3.3 Therapeutic Exercises and Activities of Daily Living

This study targets the needs and requirements of three different use cases: hyperkinetic movement disorders (HMDs), musculoskeletal injuries (MSIs), and neurological disorders such as stroke. Rehabilitation progress is achieved through different types of intensive exercises of the upper limb during a series of therapy sessions. It should be noted that upper limb therapeutic exercise sessions focus on different types of repetitive sets of either specific movements or daily living activities. The user group ranges from young children (mainly people with dystonia) to older adults (stroke patients).

Examples of movement-based therapeutic exercises include practicing (1) wrist flexion and extension, (2) essential elbow flexion and extension, and (3) finger flexion (as fingers spread or stretch) and extension (grasping or closed fingers). The wrist- and finger-based movement exercises are the main focus for both MSIs and stroke disorders. On the other hand, upper limb ADL include the areas of (1) self-care, (2) kitchen activities, (3) mobility, and (4) leisure. The number of upper limb therapy sessions varies depending on the user requirements. The movement-based exercises are performed using the injured or paretic hand, and daily living activities are performed using either one or two hands.

3.4 Sensors to Recognize Therapeutic Movements

According to the literature, there are several options that exist for choosing an appropriate sensing mechanism to capture therapeutic movements to enable the development of a bespoke VR controller. Inertial measurement units placed on the upper arm can collect orientation and acceleration measurements of the upper limb segments, shoulder, elbow, and forearm. The electromyographic electrodes placed below the elbow can detect hand movements. However, they require a high data rate and extensive signal processing, thus demanding higher power consumption. Therefore, an array of FSRs is used to capture both therapeutic wrist and finger movements. FSRs are lightweight and power-efficient, and they are ideal for wearable interfaces. As noted earlier, there is a variety of therapeutic movement-based exercises associated with rehabilitating the muscles of the arm, wrist, and fingers. The muscles that move the wrist and fingers are located mostly in the forearm. Fingers are connected through tendons to those muscles. Thus, a set of FSRs placed around the wrist can measure muscle activity. Superficial tendons will move as hand movements are performed, and because of their proximity to the surface of the skin, the FSRs can record the movement to classify hand and finger movements. Thus, we decided to use FSRs to capture movement-based therapeutic exercises. Furthermore, the array of FSRs will be integrated into the bespoke core controller to recognize only the wrist and finger movement-based exercises.

3.5 Standard Input Controls for Performing Activities of Daily Living

Children and young people with HMDs (dystonia) must practice daily living activities to improve in the areas of self-care, kitchen activities, mobility, and leisure. These activities are not therapeutic exercises. Thus, users with dystonia require handheld or hand-worn controllers, one or two, depending on the necessary daily task they are required to practice; for example, buttering bread might require them to use both hands, and driving a powered wheelchair using a joystick would only require them to use only one hand. Therefore, the handheld or hand-worn controllers developed for users with dystonia will require other input controls, such as triggers, a joystick, or buttons.

3.6 Input Controls for Non-therapeutic Interactions

The users or therapists might need to perform specific interactions, such as menu or navigation operations, in the VR-HABIT platform. These interactions are not therapeutic exercises or daily living activities but essential nontherapeutic interactions to set up the particular VR exercise for the users. Therefore, the standard input controls, such as joystick, triggers, and buttons, also need to be included in a secondary, nontherapeutic controller to complete these tasks, such as menu and navigation operations.

3.7 Using a Design Method for Adapting to Various Iterations

Such a design of systems demands iterative design and development, which will continue until the final phase, when the functional bespoke controller will be available to users. Therefore, a set of candidate design specifications for producing the electronic circuit boards was established. The result of this iterative design process is a set of two (single- and double-sided) types of printed circuit board designs, core electronic components, such as microcontrollers. The design requirements identified the needs of people with HMDs, MSIs, and neurological disorders and stroke, particularly the sensing mechanisms to capture the therapeutic exercises and input/output hardware requirements to develop the VR-HABIT platform. Identifying therapeutic exercises is a prerequisite task for this study to determine the appropriate sensing mechanisms to capture these movements. It was also equally crucial for this study to identify the required additional input devices to define the requirements of the electronics for the bespoke controller.

3.8 Design Requirements for Electronic Control Circuit of Bespoke Controller

The following design requirements will be considered when designing, manufacturing, and soldering the latest version of the electronic circuit board. The requirements are divided into four categories: power, connectivity, operation, and physical design (Table 2).

Category	*Design requirement*
Power	1. Battery power (rechargeable) 2. Voltage regulator 3. On-off switch 4. LED indicator of status
Connectivity	1. Programming port 2. Serial port for wired communication or for debugging 3. Bluetooth connection (separate for best performance and compatibility) 4. Inputs and outputs over two USB-C-sized connectors (each connector to be used for a different part or module)
Operation	1. Microprocessor compatible with a wide range of existing hardware/software 2. Dual H-bridge motor driver (powering and controlling up to 1+1 motors; implemented as a separate circuit for performance and safety) 3. Four-channel multiplexer allowing additional outputs to the first channel of the H-bridge motor driver outputs (effectively controlling up to 4+1 motors)
Physical design	1. Wholes for PCB mounting 2. Compact physical size 3. Bluetooth module and H-bridge in separate layers

Table 2: Design requirements.

4 RESULTS AND DISCUSSION

Having defined the design requirements and identified the design process, in this section, the main focus is on designing and producing electronic circuit boards. Therefore, in this section, electronics, schematics, board layout designs, fabrication of printed circuit boards (PCBs), identification of required electronic components, and assembly of the components on the boards are presented in detail. There are four types of electronic boards required for control of the bespoke controller (see Figure 1 for basic configuration). Each PCB is described in the following subsections separately.

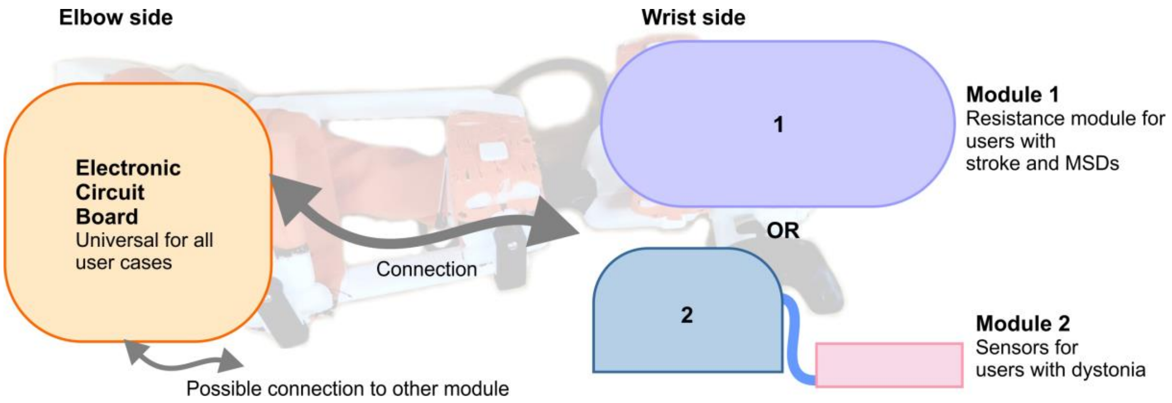


Figure 1: Basic bespoke controller configuration.

4.1 Mainboard

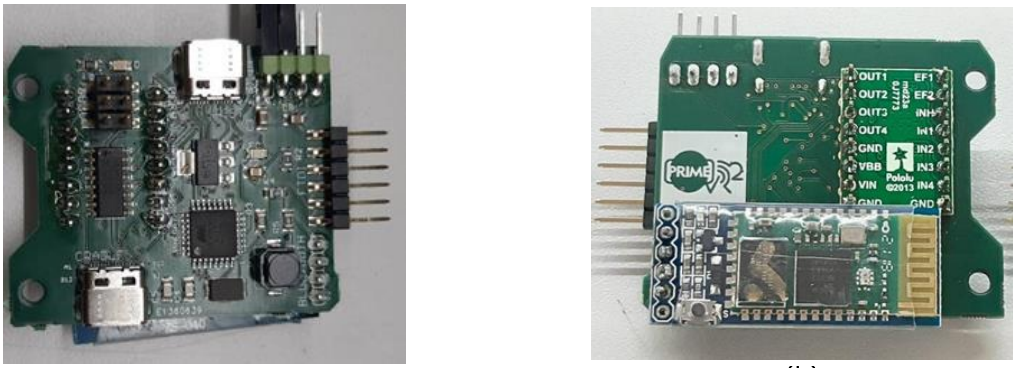
The mainboard is a double-sided PCB with an FR4 base material made of a fiberglass-reinforced epoxy-laminated sheet. The FR4 is an ideal substrate for electronic components on a PCB. Additionally, the fiberglass provides a rigid structure made even more rigid and flame-resistant by epoxy resin. The 8-bit Atmega328p microcontroller is used as the main controller, ensuring full compatibility in terms of hardware (sensors, actuators, and connectivity). The mainboard is milled using a CNC engraving machine, leaving traces where electronic components are soldered. The mainboard enables the direct integration of control of up to five motors (actuators) and various sensors (potentiometers, switches). Only some of the components are manually soldered using a mixed-method assembly process. To reduce the overall footprint, the mainboard has two USB-C connectors on the connectivity level (not on the protocol level), utilizable for connecting sensors and actuators in two different parts of the developed controller.

The mainboard includes an ATmega328p microprocessor, a dual multiplexer (2x4), a local 5V regulator, a USB-C breakout board, and a battery connector. it supports the integration of actuators for up to four DC motors and more than five potentiometers and switches

The voltage regulator provides stable power (5V DC) to all components on the mainboard and other boards (USB-C breakout boards, resistance modules, and mounting cradle circuits). The mainboard has a built-in toggle switch to turn the entire system on or off. An FTDI header is included on the mainboard to upload the program to the mainboard via a PC (through wired serial communication). The power and program uploading status are shown using the LED. Two USB-C female ports connect the mainboard with therapy (wrist/finger/dystonia) and cradle modules. In addition, the electronics design uses a standard Bluetooth BLE board (HC-05) parallel to the mainboard and a separate motor driver soldered to the mainboard (dual H-bridge motor driver IC). The Bluetooth module sends the data from the potentiometer (angle measures) to the PC. It also receives resistance values (from the PC) via a standard communication protocol to enable data exchange. This design allows for a compact layout with a small overall volume. It is also robust in terms of electronic reliability (see Figure 2). Table 3 presents the material description of the mainboard.

Number of Sides	*Base Material*	*PCB Dimension (Width/ Height)*	*Copper layer thickness*	*Mounting Holes*	*Min. Wire width*	*Min. Drill*
2	FR4	47 mm / 39 mm	0.018 mm	3 mm	0.15 mm	0.35 mm

Table 3: The mainboard description



(a) (b)

Figure 2: (a) Mainboard with (b) Bluetooth (soldered to the backside of the mainboard).

(a) (b)

Figure 3: (a) USB-C breakout boards for stroke and MSD user group and (b) dystonia user group.

Board Type	*Number of layers*	*Base Material*	*PCB Dimension*	
			Width	*Height*
USB-C Breakout (Stroke and MSI)	2	FR4	47.05 mm	29.10 mm
USB-C Breakout (Dystonia)	2	FR4	28.49 mm	25.02 mm
Straight custom-USB-C cable board	2	FR4	9.00 mm	18.85 mm
L-shaped custom-USB-C cable board	2	FR4	15.28 mm	11.00 mm
Motor and Potentiometer Boards	2	FR4	28.02 mm	20.02 mm
Potentiometer Board	2	FR4	28.02 mm	20.02 mm
Female Pogo pin board	2	FR4	33.87 mm	8.26 mm

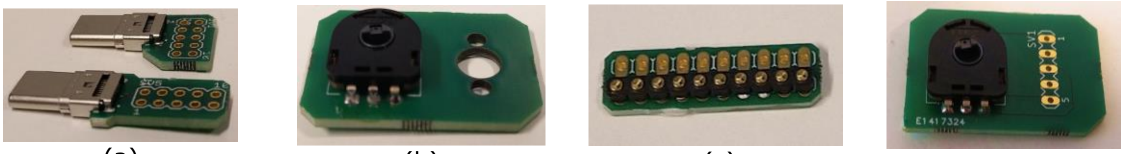
Table 4: Boards and material description.

As compared to the off-the-shelf microcontroller boards, the mainboard increases the electronic component density, enabling the direct integration of a dual multiplexer for motor control. The electronic components are automatically or in some cases manually soldered on the board using a mixed-method assembly. With the main sensing mechanisms to capture the therapeutic exercises and design structure of the core controller is established, the design requirements of the printed circuit boards and choices of electronic components, such as microcontrollers and connectors, are informing how the design evolves. The current design of the mainboard addressed the limitations of of-the-shelf circuit boards. It offers: (i) High integration of components and controls (e.g., multiplexer on board) (ii) Flexible connectivity using two USB C connectors on connectivity level (iii) Utilizes only the connectivity of the microcontroller needed for the VR-HABIT.

4.2 USB-C Breakout Boards and Custom USB-C Cables

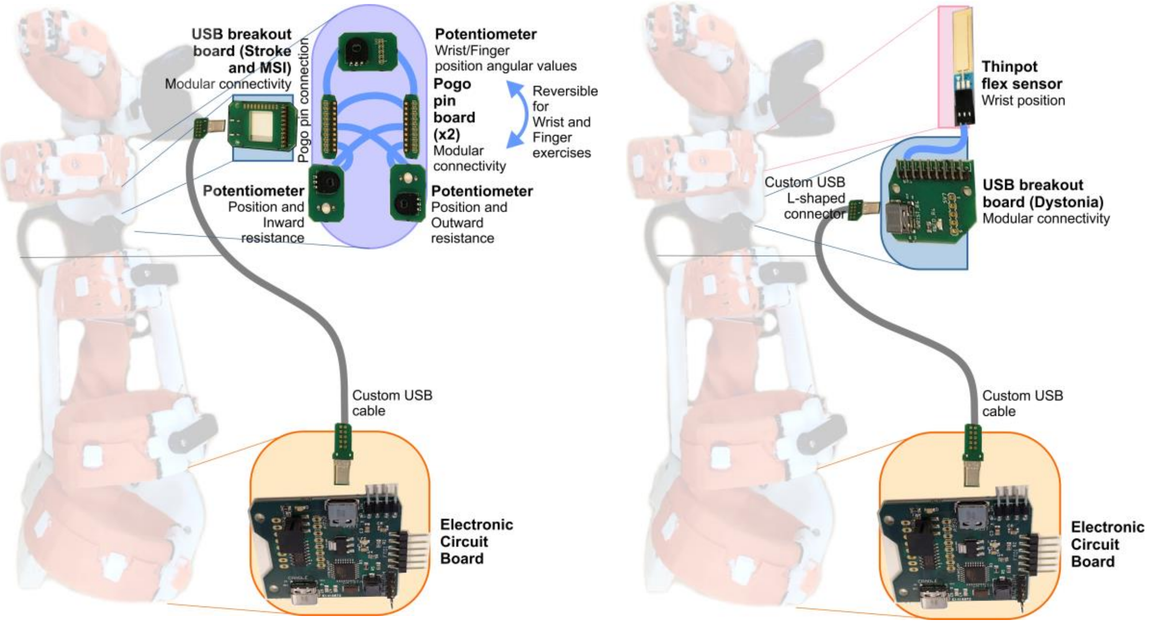
There are two different types of USB-C breakout boards, one with male pogo pins (stroke and MSIs) (see Figure 3a) and another with connection points for three different sensors (see Figure

3b). These breakout boards are placed inside the wrist module for the three bespoke controllers. These boards are connected via USB-C cables to the mainboard to control various signals, including analog data from the motor potentiometers and ThinPot position sensor and pulse-width modulation singles for the motors. Table 4 presents the material description of the fifth design iteration of the USB-C breakout boards. Two types of custom USB-C cables (straight and L-shaped) are designed and manufactured using a double-sided PCB to connect the mainboard with the USB-C breakout boards and the cradle (see Figure 4a). The material description of the custom USB-C cable boards is shown in Table 4.



(a) (b) (c) (d)

Figure 4: The custom-PCBs designed and fabricated for the resistance module: (a) two types of custom-made USB C cables (straight and L-shaped) (b) motor and potentiometer board; (c) female pogo pin board; and (d) potentiometer board for the rotary part.



(a) (b)

Figure 5: Illustration of the electronics components and their corresponding 3D-printed assembly component for the controller for users with stroke and MSIs (a) and users with dystonia (b).

4.3 Custom PCBs for the Resistance Module

Three types of custom-designed double-sided PCBs are manufactured for the resistance module: (1) to secure the potentiometers and the motors (see Figure 4b), (2) to connect the female pogo pins (see Figure 4c), and (3) to secure the potentiometer on the rotary part (see Figure 4d). These boards are manually connected by soldering American wire gauge (AWG) 26 and 28 cables. In particular, the PCBs that hold the female pogo pins are soldered via a ribbon cable (AWG 26, 10 lines). Table 4 presents the material description of the custom PCBs for the resistance module.

(a) (b) (c)

Figure 6: Mainboard mounted inside the 3D-printed controller housing (a), lithium battery inserted inside the controller housing (b), and the electronic boards, motors, and potentiometers are soldered together for the assembly process (c).

(a) (b)

Figure 7: The components are assembled inside the resistance module (a and b).

4.4 Integration of Electronics in the Controller Housings

The integration of electronics components for the bespoke controller for the stroke and MSI user group with the corresponding 3D-printed assembly part is shown in Figure 5a. Figure 5b highlights the placement and integration of the electronics components and ThinPot sensor with the corresponding 3D-printed assembly part for the bespoke controller for users with dystonia. The ThinPot sensor is inserted inside the wrist module during the 3D-printing process.

4.5 Mainboard Integration into the System and Resistance Module

The Bluetooth (HC-05) module is manually soldered together with the mainboard, which is then screw-mounted inside the 3D-printed controller housing part (see Figure 6a). The mainboard is powered using the rechargeable lithium battery inserted inside the controller housing adjacent to the mainboard (see Figure 6b). Figure 6c shows how the three types of custom-designed double-sided PCBs are manually connected by soldering different lengths of AWG 26 and 28 cables, including the PCBs holding the female pogo pins soldered via a ribbon cable (AWG 26, 10 lines). The soldering of these components is done at the FabLab Oulu facility at University of Oulu. These components weigh 38 g after securing the connections with the cables.

The soldered components are assembled inside the resistance module along with other components, including 3D-printed and mechanical parts. Figure 7 presents the assembly of these soldered components and other parts together inside the resistance module.

4.6 Limitations and Future Work

The mainboard presented in this work consists of an off-the-shelf Bluetooth module and a motor driver (see Figure 1b). In the future, designing these modules on the mainboard will not only reduce the physical dimensions of the mainboard but also make the design more efficient in terms of power consumption. Another limitation of the current design is using transistor-transistor logic (TTL) levels (0-5V) for electronic operation; therefore, in future iterations of the design, switching from TTL to complementary metal-oxide semiconductor (CMOS) voltage levels can reduce some weight of the design because the CMOS systems can work with smaller batteries. For validation of the results, the design was tested in the laboratory environment. Therefore, in the future, the authors intend to conduct an experiment on relevant patients using the current design. Such experiments can provide feedback that will improve the design and enhance usability and performance.

5 CONCLUSION

In this article, we provided a set of design principles for designing a therapeutic interaction technique for VR headsets. This article also described the process of design and integration of electronics for bespoke rehabilitation experiences and demonstrated how the electronics meet the requirements of the prototyping development process. This article also described the design guidelines and working principles and integration of custom electronics in a bespoke controller for VR rehabilitation. The suggested electronic system satisfies the criteria for custom-designed controllers and delivers patient-specific interactions. Moreover, the system enables therapists to change the degree of the rehabilitation activities based on the outputs and data of patients' performance. The impact of the study includes (1) the proposition of design guidelines for rehabilitation interactions-focused electronics and (2) the demonstration of solution meeting requirements for bespoke rehabilitation experiences. The guidelines are generalizable for electronic CAD valid for bespoke rehabilitation applications, where balance between universal elements and custom or modular solutions need to be implemented, optimizing both costs and customization.

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