D5.4
INCORPORATE EVALUATION AND FEEDBACK IN CONTROLLER ADJUSTMENT OR REDESIGN

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EXECUTIVE SUMMARY

This document summarises the outcome of task 5.6 of the PRIME-VR project as a public deliverable D5.4. This deliverable presents the PRIME-VR2 developed bespoke VR controllers to improve the therapeutic experience for users with Stroke, Musculo Skeletal Injury, and Dystonia. This document summarises the design and working principle of the two PRIME-VR2 bespoke controllers, a user evaluation study conducted with 12 healthy frequent VR users at the University of Oulu and a brief outline of the final evaluation conducted in three living labs.

Besides, the custom-designed and developed printed electronic circuit boards, including the mainboard and other boards and electronic components for the bespoke VR controllers, are explained in this deliverable.

Lastly, D5.4 summarises the findings from a series of user evaluation studies conducted with healthy, frequent VR users at the University of Oulu, users with Stroke, Musculo Skeletal Injury, and Dystonia and in three living labs. These user evaluation studies aimed to investigate the use of the PRIME-VR2-developed bespoke controllers for upper-limb rehabilitation, particularly for shoulder, wrist, and finger therapies using the custom-developed VR games. D5.4 concludes by incorporating the evaluation and feedback from a wide range of users to recommend significant improvements to the design and functionality of the bespoke controllers. Since this is a public deliverable, several critical findings of the PRIME-VR2 project are not discussed in detail.

BACKGROUND

This deliverable presents the bespoke controllers developed by PRIME-VR2 for Stroke, MSI and Dystonia users. These bespoke controllers, which consist of custom-designed, developed electronic components, aim to improve the therapeutic experience for users in performing a wide range of upper limb therapeutic movements. The leading contributing partner of this deliverable is the University of Oulu (UOO) – also responsible for designing and fabricating electronic circuit boards and interaction aspects of the bespoke VR controllers. Thus, this document also presents the electronic circuit boards designed and assembled for the two bespoke controllers.

D5.4 mainly delivers the PRIME-VR2 project tasks 5.6. The main focus of the T5.6 is to ensure the hardware and software performance of the design and functional aspects of the bespoke controllers. The developed bespoke controllers are evaluated with both healthy and actual users to incorporate the evaluations from the users and their feedback to recommend any further improvements required to the design and functionality of the bespoke controllers.

The incorporation of the feedback from users to improve the electronic design and development of the bespoke controllers reported in this deliverable is fundamental to the other subsequent critical aspects of the PRIME-VR project. As such, D5.4 directly relates to the activities of the following Work Packages: WP3 (design and development of the bespoke controller), WP4 (manufacture and assemble the bespoke controllers) and WP6 (development of VR games and VR-HABIT platform).

1 INTRODUCTION

In more recent years, the use of Virtual Reality (VR) for rehabilitation has gained much interest and is increasingly used for upper limb rehabilitation as a supportive addition to conventional physical therapy (e.g., [2,10,18,19]). The interactive, game-like, immersive simulation experience motivates the users and encourages them to explore, enjoy, and spend more time practicing the therapeutic exercises and improving treatment adherence, ultimately resulting in an improved overall experience (e.g., [14]). Prior works have focused almost solely on either commercial (e.g., [8,12]) or custom-made interfaces (e.g., [6]), games and virtual environments (e.g., [8]) for upper limb rehabilitation in immersive VR. These studies often validate the performance of their proposed system with healthy adults or with actual users. However, despite the availability of a wide range of design implications for developing upper limb rehabilitation systems, including input devices and games for immersive VR, these design recommendations are always from one type of user, either novices or healthy ones. Thus, it remains challenging for the designers and developers to integrate these solutions into a wide range of VR-based rehabilitation systems.

To facilitate the assimilation of recommendations from both expert and novice users, particularly for bespoke VR controllers for therapeutic purposes, we conducted a user evaluation study with healthy, frequent VR users with bespoke VR controllers developed specifically for rehabilitation purposes. Our work leverages the benefits of having suggestions and opinions from non-primary but expert users (healthy adults in our case) of the VR available for the designers of the bespoke controllers for rehabilitation purposes. To achieve this, in addition to the actual users, we also conducted a user evaluation study with healthy adults who are also frequent VR users.

In this deliverable, we present the bespoke VR controllers designed and developed by PRIME-VR2 to improve the therapeutic experience for users with Stroke, Musculoskeletal Injury, and Dystonia and our methods for conducting experiments with expert users. Our user evaluation study with frequent VR users utilised a spare, bespoke controller with two therapy modules with custom-designed simple VR environments. Twelve frequent VR users, who are also university students, were recruited to validate the performance of the PRIME-VR2 bespoke controllers for the wrist flexion, extension, reach, and grasp therapeutic exercises. Their interaction experience using the bespoke VR controllers in terms of usability, wearable comfort, and subjective rating of the PRIME-VR2 controllers on ease of use to perform the therapeutic exercises was collected in a dedicated laboratory study. In addition, this document summarises the design and working principle of the two PRIME-VR2 bespoke controllers, the custom-designed and developed dedicated electronics components, including the mainboard and other components boards for the bespoke VR controllers. Finally, D5.4 concludes by incorporating the evaluation and feedback from a wide range of users – the main outcome of this deliverable D5.4 – to recommend significant improvements to the design and functionality of the bespoke controllers.

2 CONCEPTS AND TERMINOLOGY

2.1. Glossary of Concepts and Terminology

This section presents below an alphabetically ordered list of definitions for the concepts and terminology used in this report.

A joystick is an input device consisting of a stick that pivots on a base and reports its angle or direction to the device it is controlling.

Base Material is the insulating material (either rigid or flexible) as well as the copper foils bonded on one or both sides. It is a synonym for copper-clad laminate, i.e., the basic raw material for PCB manufacture. This also supports all components after assembly.

Base Material Thickness is the thickness of the base material, excluding metal foil or material deposited on the surfaces.

Bluetooth Bluetooth is a short-range (up to 10 m) 2.4 GHz wireless connectivity standard intended for such applications as wireless personal area networks (PANs). These PANs can be used to exchange data between devices such as cellphones, digital cameras, printers, IoT sensors and household appliances at data rates of up to 3 Mbit (megabits per second).

Board Thickness is the overall thickness of the base material and all conductive materials deposited thereon.

Comfort Rating Scale (CRS) measures wearable comfort across six dimensions. These dimensions are Emotion, Attachment, Harm, Perceived Change, Movement and Anxiety.

Component Density is the quantity of components on a unit area of printed board.

Component Hole is a hole in a PCB through which a component lead passes in order to be soldered or connected mechanically to the printed circuit and electrically to the conductive pattern. Synonym: mounting hole. The hole is used for the attachment and electrical connection of component terminations, including pins and wires, to the printed board.

Component is any of the basic parts used in building electronic equipment, such as a resistor, capacitor, DIP or connector, etc.

Component side (Primary side) is the surface layer of a board on which most of the components are placed. Component side is also referred to as the top side (layer one-counting downwards) of the board.

Conductor Layer is the total conductive pattern formed upon one side of a single layer of base material.

DIP Soldering is a process whereby printed boards are brought into contact with the surface of a static pool of molten solder for the purpose of soldering the entire exposed conductive pattern in one operation.

Double-sided Assembly is a PCB with components mounted on both sides.

Double-sided Board is a printed board with a conductive pattern on both sides.

Drills are solid, carbide cutting tools designed specifically for the fast removal of material in extremely abrasive, glass-epoxy materials.

FR4 is a flame-retardant laminate made from woven glass fiber material impregnated with epoxy resin.

HTC Vive and Valve Index controllers are a pair of tracked controllers that give a hand presence in VR. Touch controllers feature traditional action buttons, thumb-sticks, and analog triggers that add familiarity to new experiences.

HTC Vive is a virtual reality headset developed by HTC and Valve. The headset uses "room-scale" tracking technology, allowing the user to move in 3D space and use motion-tracked handheld controllers to interact with the environment.

Layer One in a series of levels in a board on which tracks are arranged to connect components. Vias connect tracks and zones between layers.

Mounting Hole is a hole used for the mechanical mounting of a printed board or for the mechanical attachment of components to the printed board.

Packaging Density is the quantity of functions (components, interconnection devices, mechanical devices) per unit volume, usually expressed in qualitative terms, such as high, medium, or low.

Pin is a terminal on a component. A component lead that is not readily formable without being damaged.

Pinhole is a minute hole through a layer of pattern.

Pinholes are small imperfections which penetrate entirely through the conductor and/or solder.

Plated Through-hole is a hole with the deposition of metal (usually copper) on its sides to provide electrical connections between internal or external conductive patterns.

Printed Board Assembly is a printed board with electrical or mechanical components, other printed boards, or a combination of these, attached to it with all manufacturing processes, soldering, coating, etc. completed.

Printed Board is the general term for completely processed printed circuit or printed wiring configuration. It includes single, double, and multi-layer boards, both rigid and flexible.

Printed Circuit Assembly is a printed circuit board to which discrete components, hardware, and other electronic devices have been attached to form a complete operating unit.

Printed Circuit Board (PCB) is an insulating material onto which an electronic circuit has been printed or etched.

Printed Circuit is a circuit where the interconnections between components, terminals, sub-assemblies, etc., are made by conductive strips (traces) that have been printed or etched onto an insulating board.

Signal is an electrical impulse of a pre-determined voltage, current, polarity and pulse width.

Single-image Production Master is a production master used in the process of making a single printed board.

Solder (Soft) is a metal alloy with a melting temperature that is below 450°C.

Substrate: See Base Material.

Surface Mount Technology (SMT) defines the entire body of processes and components create printed circuit assemblies without components with leads that pierce the board

Surface Mounted Device (SMD) describes any component or hardware element designed to be mounted to a printed circuit board (PCB) without penetrating the board.

Surface Mounting is the electrical connection of components to the surface of a conductive pattern that does not utilise component holes.

System Usability Score (SUS) provides a tool for measuring the usability of a wide variety of products and services, including hardware, software, mobile devices, websites, and applications. It consists of a 10-item questionnaire with five response options for respondents that allows them to evaluate a given system.; from Strongly agree to Strongly disagree in a is a Likert Scale.

Through Connection is an electrical connection between conductive patterns on opposite sides of an insulating base, e.g., plated through-hole or clinched jumper wire.

Trace is a single conductive path in a conductive pattern.

Traces are the metallic conductive strips that provide connections between components, terminals, etc., on printed circuit

Virtual Environment (VE) is a synthetic, spatial (usually 3D) world seen from a first-person point of view. The view in a virtual environment is under the real-time control of the user.

Virtual Reality (VR) is an approach that uses displays, tracking, and other technologies to immerse the user in a VE. Note that in practice VE and VR are often used almost interchangeably.

Range of motion (or ROM), is the linear or angular distance that a moving object may normally travel while properly attached to another**.**

2.2. List of Abbreviations

This section presents below an alphabetically ordered list of definitions for the concepts and terminology used in this report.

3D	Three Dimensional
ADL	Activities of Daily Living
AWG	American Wire Gauge
CPT	Conventional Physical Therapy
CRS	Comfort Rating Scale
DSPT	Double-Sided Plated Thru
ECB	Electronic Circuit Board
FTDI	Future Technology Devices International Limited
GEQ	Game Experience Questionnaire
HMD	Head-mounted display
IC	Integrated Circuit
IRED	Infrared Emitting Diodes
MR	Mixed reality
MSI	Musculoskeletal Injuries
NPTH	Non plated though-hole
OTs	Occupational Therapists
PC	Personal Computer
PCB	Printed Circuit Board
PCBA	Printed Circuit Board Assembly
PEC	Printed Electronic Component
PTH	Plated through-holes
PWB	Printed Wiring Board
ROM	Range of motion
RTS	Rehabilitation Training System

SDK	Software development kit
TPU	Thermoplastic polyurethane
UE	Upper Extremity
UI	User Interface
UL	Upper Limb
USB	Universal Serial Bus
UV-C	Ultraviolet C
VE	Virtual environment
VR	Virtual reality
VRE	Virtual reality experience

3 METHODOLOGY

We followed mixed user evaluation methods to evaluate the performance of the PRIME-VR2 bespoke controllers. Our work envisions a scenario where suggestions and opinions from non-primary but expert users (healthy adults in our case) of the system would be available for the designers of the bespoke controllers for rehabilitation purposes. To achieve this, in addition to the actual users, we also conducted a user evaluation study with healthy adults who are also frequent VR users. We used a spare, bespoke controller with two therapy modules and custom-designed simple VR environments for the evaluation study with healthy adults.

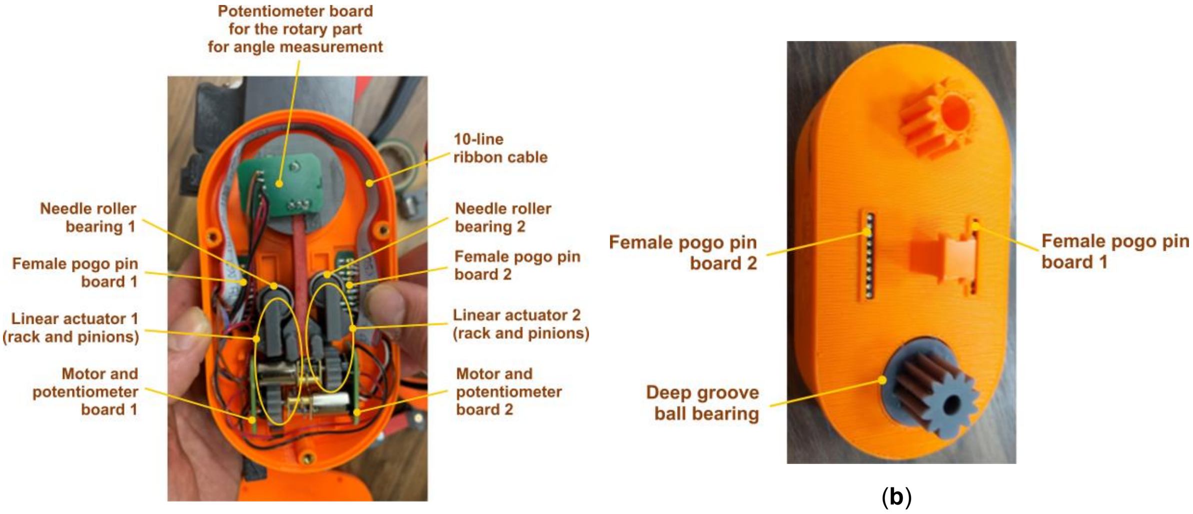
The frequent VR users, who are also university students, were recruited to validate the performance of the PRIME-VR2 bespoke controllers for the wrist flexion, extension, reach, and grasp therapeutic exercises. Their interaction experience using the bespoke VR controllers in terms of usability, wearable comfort, and subjective rating of the PRIME-VR2 controllers on ease of use to perform the therapeutic exercises was collected in a dedicated laboratory study.

4 BESPOKE PRIME-VR2 CONTROLLERS

Two types of PRIME-VR2 bespoke controllers are designed and manufactured for MSI, Stroke, and Dystonia users. Both controllers have the following four main 3D-printed components: (1) a therapy module, which supports finger and wrist therapies, (2) a core module that houses the electronics mainboard and the power supply, (3) a spine which connects therapy and core module via a custom-designed USB-C cable, and (4) straps that are worn around the forearm and hand. While the straps, core module, and spine components are identical for both bespoke PRIME-VR2 controllers, two different therapy modules are used for the MSI/Stroke and Dystonia users. The controllers use two Vive Trackers (3.0)[1] to capture the therapeutic movements.

4.1. Controller for Users with Stroke/Musculo Skeletal Injury

The PRIME-VR2 bespoke VR controller for users with Stroke and Musculo Skeletal Injury (MSI) consists of a resistance module for finger and wrist therapy. This module measures the angle of the wrist and finger flexion/extension during therapy. WP3 designed and developed the functionalities of the resistance module and deliverable D3.4, particularly section 2.1.1, which summarises the design options and the current mechanism.



(**a**)

(**b**)

Figure 1 The resistance module: (**a**) the components inside the module; and (**b**) when the module is closed with a lid.

The current design is based on a fulcrum mechanism that utilises a pair of 3D-printed linear actuators, with each actuator comprising a circular gear (the pinion) connected with a custom-designed linear gear (the rack). Each rack has a linear gear on one end and a needle roller bearing on the other end[2]. Two standard low-power micro metal gear motors[3] are used to rotate the pinions, which causes the rack to be driven/moved in a line. The gear motors are connected with two thin 360-degree rotary potentiometers. In addition, the resistance module consists of a narrow, deep groove ball bearing[4] fixed with a rotating spine. The rotating spine

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[1] https://www.vive.com/us/accessory/tracker3/
[2] https://www.kugellager-express.de/drawn-cup-needle-roller-bearing-hk1015-open-hk1015-10x14x15-mm
[3] https://www.pololu.com/product/1094
[4] https://www.kugellager-express.de/deep-groove-ball-bearing-6705-2rs-61705-2rs-25x32x4-mm

is connected with another thin 360-degree rotary potentiometer which measures the angle when the user performs therapeutic wrist/finger flexion or extension exercises (see Figure 1).

Based on the design recommendations, WP5 designed and manufactured three types of custom-designed double-sided PCBs for the resistance module (see Figure 1): (1) to secure the thin potentiometers and the gear motors, (2) to connect the Female Pogo pins, and (3) to secure the potentiometer on the rotary part (see Table 1). These boards are manually connected by soldering AWG 26 and 28 cables. In particular, the PCBs which hold the Female Pogo pins are soldered via a ribbon cable (AWG 26, 10 lines).

Table 1 Types of electronics boards designed and manufactured for the bespoke controller for users with Stroke/MSI, placement, and weight.

Type of Board	Quantity	Placement	Weight (in grams)
Mainboard	1	Core module (controller housing)	15[1]
USB-C Breakout Board	1	Wrist module	4
Motor and potentiometer board	2	Resistance module	4
Potentiometer board (for angle measurement, fixed on the rotary part)	1	Resistance module	2
Female Pogo pin board	2	Resistance module	4
Custom USB-C Cables	1	Spine (connects core and therapy modules)	22[6]

[1] includes Bluetooth HC-05 module.

[2] includes the 10-conductor cable.

Analog readings from the potentiometer are transmitted to a microprocessor in the core module through the Pogo pins and a custom-developed USB-C cable. The processing unit comprises an ATmega328p microprocessor, dual multiplexer (2x4), dual H bridge motor driver IC, local 5v Regulator, local 5v Regulator, USB C breakout board, a Bluetooth module (HC-05), a rechargeable 2S 7.4V lithium-polymer battery with capacity of 450mAh and a battery connector [17]. The electronics module also receives resistance values (from the PC) via a standard communication protocol to allow data exchange. Figure 2 shows the PRIME-VR2 bespoke controller for the users with Stroke and MSI. The total weight of all the electronic boards, potentiometers, cables, and excluding the rechargeable battery and the pair of micro metal gear motors, is around 51g.

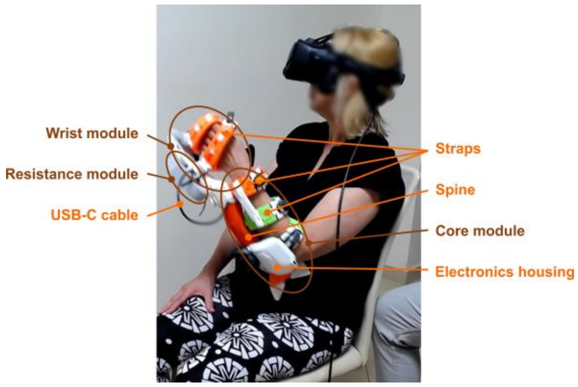

Figure 2 PRIME-VR2 bespoke left-hand controller for users with Stroke and MSI.

The details of the components, including the number of 3D-printed straps and the placement, are presented in Table 2.

Table 2 List of components of the PRIME-VR2 bespoke controller for users with Stroke and MSI.

Components	Body Part	Number of 3D-printed Straps
Core Module (consists of spine, electronics housing, and a Vive tracker[1])	Forearm	Three
Therapy (consists of wrist, resistance modules, and a Vive tracker[1])	Hand	Two

[1] Vive trackers are mounted on the bespoke controller using off-the-shelf screw mountable parts.

4.2. Controller for Users with Dystonia

The PRIME-VR2 bespoke VR controller for users with Dystonia consists of two Vive trackers and a sensor embedded in a 3D-printed flexible palm strap. WP3 designed and developed the functionalities of the palm strap, and the details are documented in section 3.4 of the deliverable D3.4.

The current design of the bespoke controller consists of a ThinPot[5] flex sensor embedded in a 3D-printed Thermoplastic polyurethane (TPU) part. Based on the design recommendations, WP5 designed and manufactured a custom-designed USB-C breakout board (double-sided) for the therapy module. Three standard 10 cm male-to-female jumper wires connect the sensor to the board (see Figure 3).

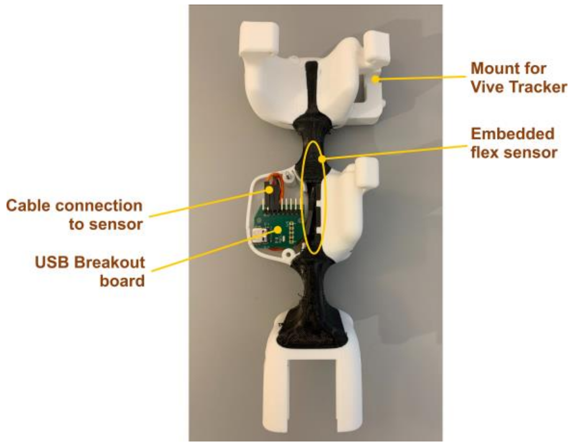

Figure 3 Inside the therapy module of the bespoke controller for the Dystonia user group.

Analog readings from the flexible ThinPot sensor are transmitted to a microprocessor in the core module through the custom-developed USB-C cable. This controller also uses the same mainboard developed for the controller for Stroke and MSI users. Thus, the processing unit comprises an ATmega328p microprocessor, dual multiplexer (2x4), dual H bridge motor driver IC, local 5v Regulator, Bluetooth (HC-05), USB C breakout board, 7.4V lithium-polymer battery and a battery connector. Table 3 presents the number of electronic boards in this controller.

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[5] https://www.spectrasymbol.com/product/thinpot/

Table 3 Types of electronics boards designed and manufactured for the bespoke controller for users with Dystonia, placement, and weight.

Type of Board	Quantity	Placement	Weight (in grams)
Mainboard	1	Core module (controller housing)	15[1]
USB-C Breakout Board	1	Wrist module	3
Custom USB-C Cables	1	Spine (connects core and therapy modules)	22[2]

[1] includes Bluetooth HC-05 module.

[2] includes the 10-conductor cable.

Figure 4 shows the PRIME-VR2 bespoke controller for users with Dystonia. However, this controller does not need a dual multiplexer (2x4) or dual H-bride motor drivers. We used the same board in order to save the design and manufacture time of a specific board, which also needs significant time to spend on the design of the 3D-printed housing part. The total weight of all the electronic boards, ThinPot sensor, cables, and excluding the rechargeable battery, is around 40g.

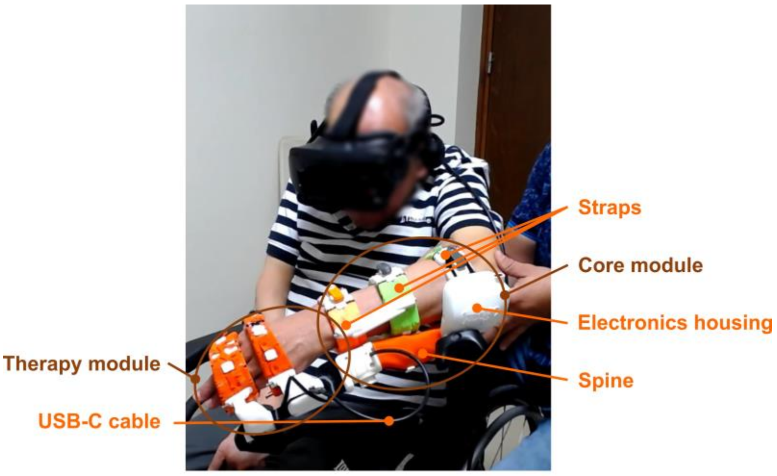


Figure 4 PRIME-VR2 bespoke left-hand controller for users with Dystonia.

Table 4 details the components, including the number of 3D-printed straps and where the straps are placed on the user's body.

Table 4 List of components of the PRIME-VR2 bespoke controller for users with Dystonia.

Components	Body Part	Number of 3D-printed Straps
Core Module (consists of spine, electronics housing, and a Vive tracker[1])	Forearm	Three/Two
Therapy (consists of a ThinPot sensor and a Vive tracker[1])	Hand	Two

[1] Vive trackers are mounted on the bespoke controller using off-the-shelf screw mountable parts.

4.3. Electronics Designed for the Bespoke Controllers

The electronics for the bespoke controller for Stroke, MSI, and Dystonia users consists of two types of boards (mainboard and USB-C breakout board) connected via a custom-designed USB cable. All boards are double-sided printed circuit boards (PCB) with an FR4 base material made of fibreglass-reinforced epoxy-laminated sheet. FR4 is a flame-retardant laminate made from woven glass fiber material impregnated with epoxy resin. It is an ideal substrate for electronic components on a PCB. Also, the fibreglass provides a rigid structure made even more rigid and flame-resistant by epoxy resin. The boards are milled using a CNC engraving machine, leaving traces where electronic components are soldered. All these boards are designed, manufactured, and soldered at the University of Oulu.

Once designed, it takes approximately 30 human hours (for a person with 5-6 professional experience) to produce and test one copy of the custom-made electronic boards for the bespoke PRIME-VR2 stroke/MSI controllers. The time to produce and test one copy of the custom-made electronic boards for the bespoke PRIME-VR2 dystonia controller is approximately 12 hours. One copy of the custom-made electronic boards for bespoke PRIME-VR2 stroke/MSI controllers produced in very small quantities (1-3 copies at a time) costs approximately 280 euros, excluding the motors. While one copy of the custom-made electronic boards for bespoke dystonia controllers produced in minimal quantities (1-3 copies at a time) costs approximately 210 euros. This does not include the human hours, such as salary and others. High volume production of electronic boards and connections can significantly reduce the manufacturing cost of the boards. Larger orders of the components, such as microcontrollers or dual H-bridges used in the electronic boards, would further reduce the costs.

4.3.1. Mainboard

The mainboard enables the direct integration of control of up to 5 motors (actuators) and various sensors (potentiometers, switches). Only some of the components are manually soldered using a mixed-method assembly process. The mainboard has two USB C connectors on the connectivity level (not on the protocol level) in order to reduce the overall footprint in the PCB design. These connectors are utilisable for connecting sensors and actuators in two different parts of the developed controller.

(**a**) (**b**)

Figure 5 The board designed for the PRIME-VR2 controllers: (**a**) mainboard with (**b**) Bluetooth HC-05 (soldered at the backside of the mainboard).

The mainboard is placed inside the Core Controller housing, which includes an ATmega328p microprocessor, dual multiplexer (2x4), dual H bridge motor driver IC, local 5v Regulator, Bluetooth (HC-05), USB C breakout board, and a battery connector. In addition to the battery connector, a power button is implemented. The pins for battery and power button on the right top end of the board can be seen in Figure 5**a**. An 8-bit Atmega328p microcontroller is used, ensuring full compatibility in terms of hardware (sensors, actuators, and connectivity). The same mainboard is used for all three bespoke controllers, and it is capable of operating the motors in the cradle unit (see Figure 5).

Table 5 presents the material description of the electronic circuit board used in the PRIME-VR2 controllers.

Table 5 The PRIME-VR2 controller mainboard and material description.

Number of Sides	Base Material	PCB Dimension		Outer Layer Copper Foil	Holes Size
		Width	Height		
2	FR4	39 mm	47 mm	18µm (End-Cu +/-35µm)	0.45 mm

4.3.2. USB-C Breakout Boards

Two different types of USB C breakout boards, one with male Pogo pins (see Figure 6**a**) and another with connection points for three different sensors (see Figure 6**b**), is made for the PRIME-VR2 bespoke controllers. These breakout boards are placed inside the therapy modules of the two bespoke controllers. These boards are connected via USB-C cable to the mainboard to control various signals, including analog data from the motor potentiometers and ThinPot sensor and PWM singles for the motors.

(**a**) (**b**)

Figure 6 The USB-C breakout boards for the PRIME-VR2 controllers: (**a**) Stroke and MSI users and (**b**) Dystonia users.

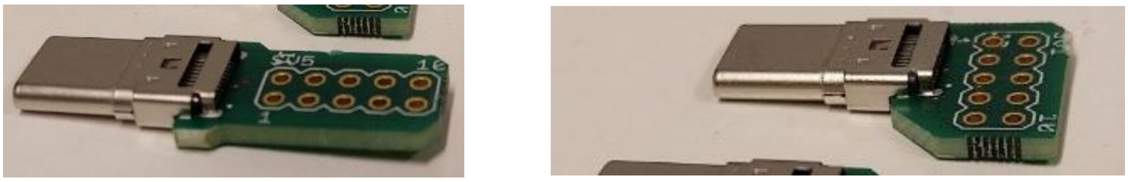
Table 6 presents the material description of the two USB-C breakout boards used in the PRIME-VR2 controllers.

Table 6 The ECB 5 USB-C breakout boards and material description.

Board Type	Number of Sides	Base Material	PCB Dimension	
			Width	Height
USB-C Breakout (Stroke and MSI)	2	FR4	47.05 mm	29.10 mm
USB-C Breakout Board (Dystonia)	2	FR4	28.49 mm	25.02 mm

4.3.3. Custom-USB-C Cables made for the PRIME-VR2 controllers

Two types of custom-USB-C cables (straight and L-shape) are designed and manufactured using a double-sided PCB to connect the mainboard with the USB-C breakout boards and the cradle unit (see Figure 7).



(**a**) (**b**)

Figure 7 Two types of custom-made USB C cables: (**a**) straight and (**b**) L-shaped.

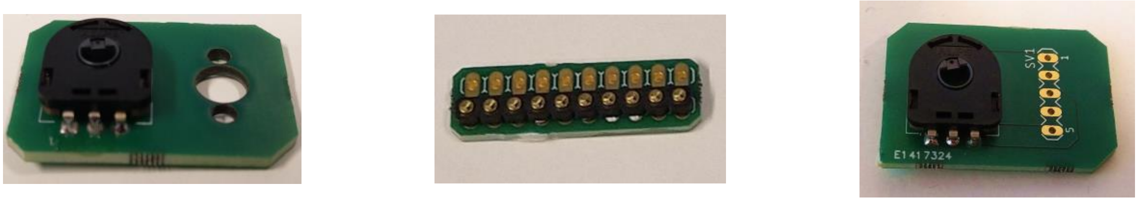
The material description of the custom-USB-C cable boards is shown in Table 7.

Table 7 The PRIME-VR2 custom-USB-C cable boards and material description.

Board Shape	Number of Sides	Base Material	PCB Dimension	
			Width	Height
Straight	2	FR4	9.00 mm	18.85 mm
L-shaped	2	FR4	15.28 mm	11.00 mm

4.3.4. Custom PCBs for the Resistance Module

Three types of double-sided PCBs are custom-designed and manufactured for the resistance module: (1) to secure the potentiometers and the motors (see Figure 8**a**), (2) to connect the Female Pogo pins (see Figure 8**b**), and (3) to secure the potentiometer on the rotary part (see Figure 8**c**). These boards are manually connected by soldering AWG 26 and 28 cables. In particular, the PCBs which hold the Female Pogo pins are soldered via a ribbon cable (AWG 26, 10 lines).



(**a**) (**b**) (**c**)

Figure 8 The custom-PCBs designed and fabricated for the resistance module: (**a**) motor and potentiometer board; (**b**) female pogo pin board; and (**c**) potentiometer board for the rotary part.

Table 8 presents the material description of the custom PCBs of the resistance module.

Table 8 The custom-PCBs of the resistance module and material description.

Board Type	Number of Sides	Base Material	PCB Dimension	
			Width	Height
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

4.4. Summary

Two types of identical PRIME-VR2 bespoke controllers are designed and manufactured for MSI, Stroke, and Dystonia users. While the straps, core module, and spine components are identical for both bespoke PRIME-VR2 controllers, two different therapy modules are used for the MSI/Stroke and Dystonia users. The controllers use two Vive Trackers (3.0) to capture the therapeutic movements. In addition, these forearm/hand-worn controllers consist of custom-made electronic components. The processing units of the PRIME-VR2 controllers consist of an ATmega328p microprocessor. In addition, the mainboard also includes a dual multiplexer (2x4), dual H bridge motor driver IC, local 5v Regulator, Bluetooth (HC-05), USB C breakout board and a battery connector. The electronics for the bespoke controller for Stroke, MSI, and Dystonia users consists of two types of boards (mainboard and USB-C breakout board) connected via a custom-designed USB cable. All these boards are designed, manufactured, and assembled at the FabLab and other facilities at the University of Oulu. Solutions based on predominantly off-the-shelf boards can be cheaper compared to very low-volume production of custom-made electronic boards. Mass production of custom-made boards can bring the costs to the level of off-the-shelf boards. Furthermore, the initially assembled bespoke controller with the Stroke/MSI and Dystonia therapy modules was evaluated with 12 healthy frequent VR users. The detail of the initial user evaluation conducted with the healthy adults is summarised in the following section.

5 USER EVALUATION (HEALTHY ADULTS)

The main objective of the user evaluation experiment with healthy frequent VR users was to explore the usability of the PRIME-VR2 righthand controllers in performing therapeutic exercises. During this study, all participants were asked to try the two PRIME-VR2 controllers on their right hand.

5.1. Virtual Environments and Exercises

In order to validate the PRIME-VR2 controllers to perform therapeutic exercises/movements in VR, we utilized a slightly modified version of the virtual environment reported in the deliverable D5.3 using the Unity game engine version 2021.1.22f. As reported in D5.3, the interaction design, virtual scene, and objects are chosen based on their natural relationship with the chosen therapeutic exercises. Thus, for this study, we only used a virtual scene where the user is tasked to move a pate of Pizza from one side of the dining table to the other and vice versa. Thus, the same virtual scene and task were used for both controllers or, in other words, using two interaction methods, wrist flexion/extension and reach and grasp movements. There is specified finish/target location was used for this study to allow users to move as much as they can using the PRIME-VR2 controllers. We adopted this approach to explore the users' maximum range-of-motion (ROM) of the wrist using the PRIME-VR2 controllers with different resistance.

5.2. Measures

The measures used in the evaluation study include logged data, questionnaires, observations, and semi-structured interviews.

1) We measured the wearable comfort (wearability) of the PRIME-VR2 controllers and Valve index headset using the comfort assessment method developed by Knight et al. [11], which measures the comfort aspect of wearable devices in 6 different cognitive and physical dimensions (see Table 9). Each of these six dimensions of comfort is measured using a 21-point comfort rating scale (CRS) from 1 (Low) to 21 (High). We adopted the original dimensions and the statements for each category for this study.

Table 9 Comfort dimensions and descriptions.

Dimension	Description
Emotion	Concerns about the appearance
Attachment	Physical feel of the device on the body
Harm	Physical affect
Perceived Change	Physically feeling different
Movement	Physically affects the movement
Anxiety	Worried about the device – other fears

2) To measure the usability of the PRIME-VR2 controllers with a VR headset, we adopted the standard System Usability Scale (SUS) [20], which produces a total score ranging from 0 to 100, with higher values indicating higher usability. It consists of a 10-item questionnaire with five response options (Strongly Agree to Strongly Disagree) for respondents.
3) Participants' subjective rating of the PRIME-VR2 controllers on ease of use in performing the exercises was collected as a rating between 1 (very poor) and 10 (very good).

5.3. Participants

Twelve (7 males, 5 females) healthy adults aged between 21 and 32 years volunteered for the study. They are university students (bachelor and master) from different educational backgrounds, including Information Technology and Electrical Engineering, Education, Business, and Medicine. None of them is left-handed. They are all familiar with VR and have experience with a wide range of VR headsets and controllers, including Oculus Rift, HTC Vive, and Valve Index. Before this study, they all had experience with at least one movement-based interaction device, such as Nintendo Wii or Microsoft Kinect.

5.4. Apparatus

The user evaluation of the PRIME-VR2 controllers with healthy frequent VR users was conducted in a dedicated VR experiment lab. A righthand PRIME-VR2 controller with therapy modules for Stroke/MSI and Dystonia users was used for this study. Each participant was standing in a marked spot, and a Valve Index VR headset[6] was used as a display device with PRIME-VR2 controllers. A Legion VR laptop was to connect the VR headset. The bespoke controller and therapy modules were sanitised after each user with the CleanBox[7] UV-C disinfecting device.

5.5. Procedure

The study process included four stages for each participant: intro, study with Stroke/MSI controller, study with Dystonia controller, and post-study. During the introduction stage, the participants were asked to complete their demographic and background details. Following this, each participant was given a brief introduction to the PRIME-VR2 controllers and the experiment procedure. They all started the experiment with the controller made for the Stroke/MSI. For each controller, a short video clip was used to demonstrate the exercises/movements; for instance, only reach and grasp exercises were demonstrated for the Dystonia controller. During the second phase, the participants were asked to perform wrist flexion and extension movements three times with four different resistance levels. The resistance levels were always presented in the same order, starting from default to level three for all participants. Thus, each participant was asked to perform wrist flexion three times in all four resistance levels, followed by extension movements. In a similar way, they were asked to perform finger flexion and extension movements. After this phase, a researcher helped the participants to change the therapy module to perform three times reach and grasp exercises with the controller made for Dystonia users. A short 3-5-minute break was provided for each participant between these two phases. In the final phase, participants completed their subjective feedback on the controllers and shared their experiences and feedback in the semi-structured interview. We disinfected the controller, therapy modules, and VR headset using a Cleanbox UV steriliser after each user. The entire experiment process lasted about 40-50 minutes for each participant.

5.6. Results

Our results include each participant's wearable comfort with the PRIME-VR2 bespoke controllers, the VR headset, system usability sore, and range of motions for wrist flexion and extension movements.

5.6.1. Wearable Comfort

The healthy frequent VR users scored their level of comfort on a 21-point scale [11] from 0 to 20 after performing wrist, finger flexion, extension, reach and grasp exercises using the controller made for the Stroke/MSI and Dystonia users, respectively. The mean CRS scores ranged from 6.2±1.5 to 19.7±0.5 depending on the comfort dimension and the PRIME-VR

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[6] https://store.steampowered.com/valveindex

[7] https://cleanboxtech.com/products/

righthand prototypes. The Attachment (18.63±1.9) dimension received the overall highest average score, followed by the Perceived change (14.96±2.13), Emotion (14.44±3.64), and Movement (13.10±4.96) for both PRIME-VR2 bespoke controllers. The lowest overall CRS score for both controllers was for the Harm dimension at 6.33±1.40. Figure 9 shows the mean comfort rating scale (CRS) for the six comfort dimensions for the bespoke PRIME-VR2 controllers.

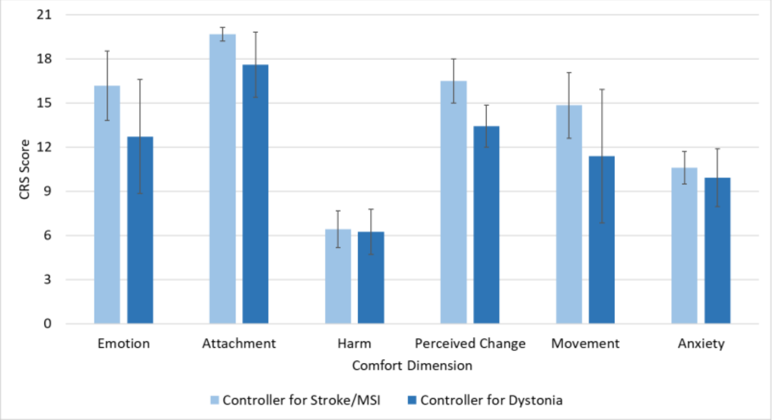


Figure 9 Comfort Rating Scale score for the Valve Index headset and controllers.

5.6.2. Usability of the Bespoke Controllers

The average SUS score for the standard VR headset and bespoke controller for stroke and MSI users was 59.42, and for the Dystonia users, 46.75 out of 100, suggesting that the current design had closer to an acceptable level of usability from the perspective of these frequent healthy VR users (see Figure 10).

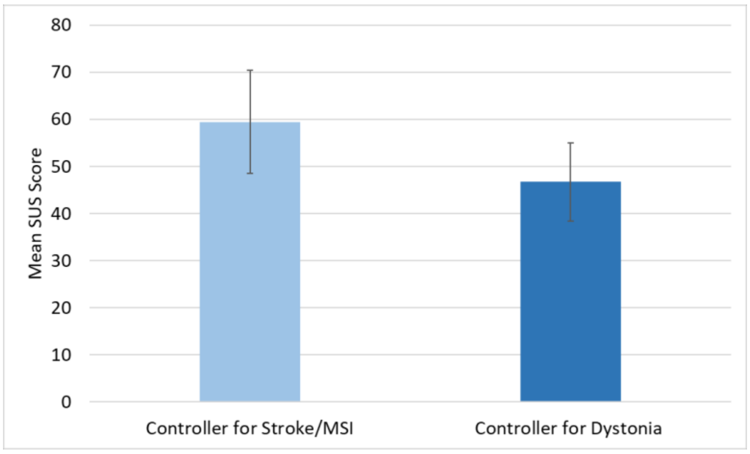


Figure 10 SUS Score for PRIME-VR2 bespoke controllers given by the healthy frequent VR users.

5.6.3. Resistance Levels

We evaluated the ability to perform effective wrist flexion and extension with four different resistance levels. As reported in [9], we defined the range of motion (ROM) for the wrist movements with a maximum angle of 60° for wrist flexion and 45° for wrist extension. Figure 11 presents the results of the range of motion for the wrist flexion and extension with four different resistance levels provided by the PRIME-VR2 therapy module of the controller for users with Stroke/MSI. Our results showed that the increased resistance level limits the ROM angle for both wrist flexion and extension for healthy adults. With more resistance provided, a lower angle was achieved by frequent VR users. We did not use finger flexion and extension as it was not possible for the users to perform finger extension from a neutral position (straight line).

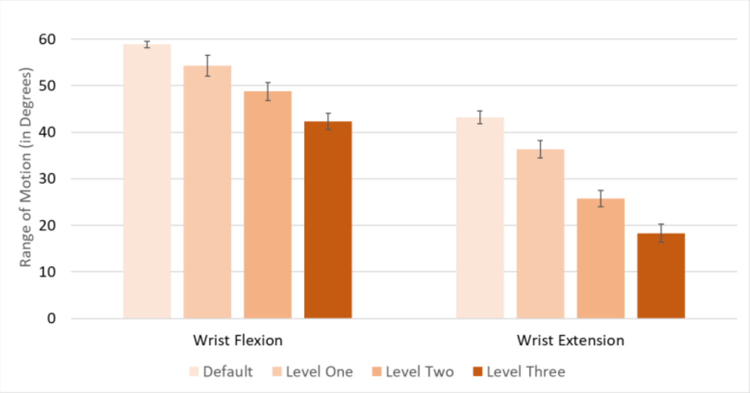


Figure 11 The range of motion of wrist flexion and extension movement with different resistance levels.

5.6.4. Subjective Rating on Ease of Use

By comparing the subjective rating for ease of use between the two PRIME-VR2 controllers, we found that the healthy, frequent VR users rated the controller for users with Dystonia (*M*=4.9; *SD*=1.02) in ease of use slightly more highly than the controller for the Stroke/MSI user group (*M*=4.3; *SD*=1.14). However, their ratings were not significantly different between the two bespoke PRIME-VR2 controllers ($p>0.05$).

5.6.5. User Feedback

During the evaluation session, the frequent VR users informed us of their feedback on using the PRIME-VR2 bespoke controllers to perform wrist flexion, extension, reach, and grasp movements. They are all aware that the controllers are used for people with special needs. However, all users perceived that performing these movements, including wrist and shoulder, with the current version of the PRIME-VR2 controllers is somewhat complicated and cumbersome. All of them highlighted that the controllers decreased their ability to lift and perform wrist movements in the air naturally. They also reported that the given resistance is slightly high for them to perform the movements, especially when the therapy (resistance) module is heavy. Though all 12 users mentioned it is easy to learn how to use two controllers, they mentioned that sufficient time and practice are required to wear the controller on their forearm and hand independently. They all reported that the current version of the bespoke controllers is heavy, and using it for a long time is almost impossible. Though they lighted the colour of the controllers, they felt strange wearing these devices. They also highlighted that the number of straps used in the controllers should be reduced to two or three maximum, and more importantly, the locking mechanism should be easy and simple to use.

5.6.6. Issues with Resistance Module

During the user study with the healthy adults, it was observed that the gear mechanism influenced the position of the Pogo pins inside the resistance module (see Figure 12). This issue obviously resulted in the failure of the gear mechanism and the disconnection of the same from the mainboard. These issues were observed, mainly when the resistance levels were changed to using the PC while the user was still wearing the controller.

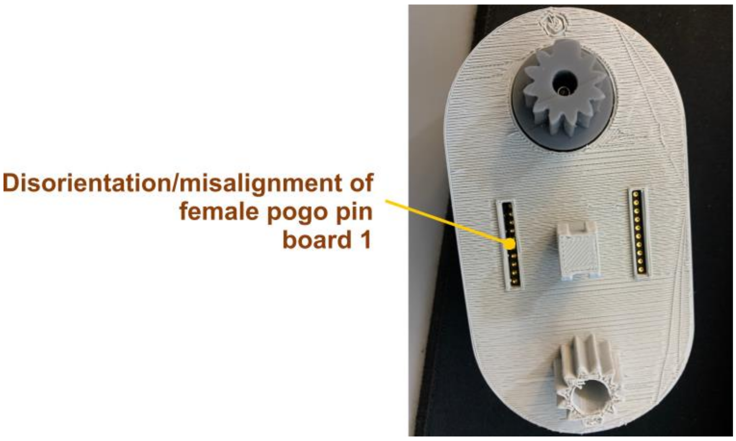


Figure 12 Disorientation of the Pogo pins on the resistance module during the change of resistance levels.

On the other hand, WP4 performed a simulation of the free fall of the resistance module before the participants used the controllers at the living labs. The resistance module was dropped once in the planar (flat) position, sideways and along its longest axis from a height of 0.7m. The intensity of the damage following the free-fall test is detailed in Section 10.2 of the deliverable D4.4. The key results related to the functionality of the resistance module are briefly outlined below.

Though the material and the structure resisted the impact of the free-fall test from a height of 0.7m, significant issues and damages were noted when the module was opened. In particular, two of the four structural pillars of the lid, which hold the Female Pogo pin boards, were completely broken into two pieces (see Figure 13).

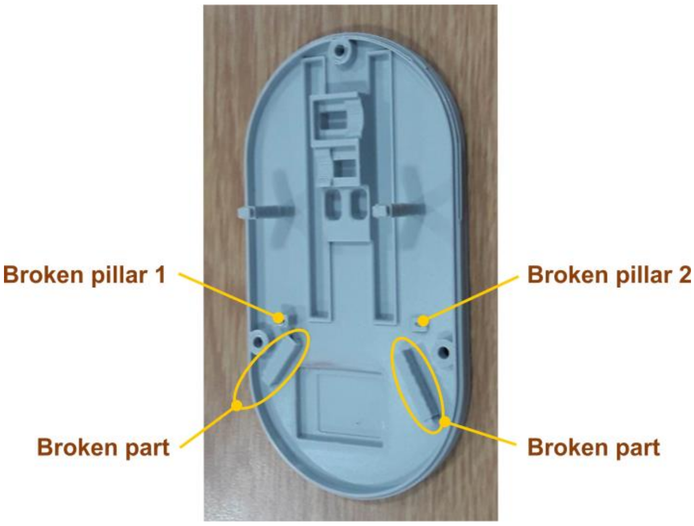


Figure 13 The two broken pillars on the lid of the resistance module.

Another significant impact of the drop test was the failure of the custom-designed linear gear mechanism, particularly the damaged circular gears (see Figure 14), which ultimately turned the resistance module non-functional.

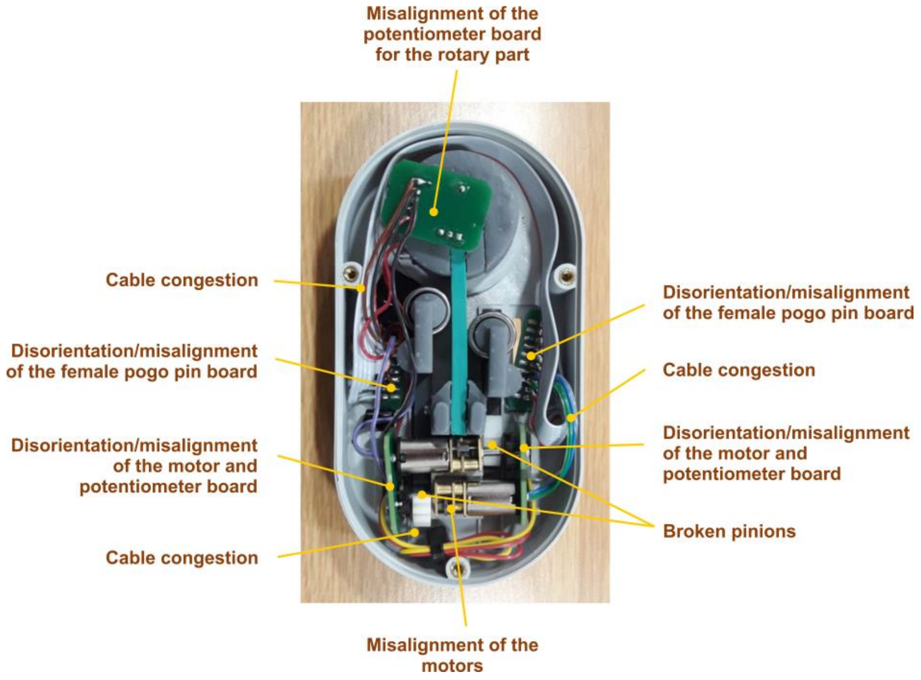


Figure 14 The damaged custom-designed linear gear mechanism and other parts inside the resistance module.

5.6.7. Limitations

The performed study used one of the initial versions of the PRIME-VR2 test controllers with a Valve Index VR headset with healthy frequent VR users. These devices were not designed for the participants who tried them during the study. They are healthy adults and familiar with different VR controllers. Testing the controllers with participants with no prior knowledge/experience/exposure with VR, as this might be the case with actual PRIME-VR2 users, could have increased the validity of the study.

5.7. Summary

Virtual Reality based upper-limb rehabilitation training systems have gained much interest and are increasingly used for hand rehabilitation as a supportive addition to conventional therapy (e.g., [3–5]). Prior works have focused almost solely on either commercial (e.g., [1,8]) or custom-developed (e.g., [7]) interfaces for hand rehabilitation in VR. The main objective of this user evaluation was to explore the performance of the bespoke controllers developed for three different user groups.

6 USER EVALUATION AT LIVING LABS

6.1. Overview

The final evaluation of the PRIME-VR2 bespoke controllers for the three user groups and the VR games was conducted independently at the three living labs. A total of 4 PRIME-VR2 bespoke controllers were used at this evaluation stage, including right and left-hand users. Out of these, three controllers are made explicitly for three users (one at each living lab) using their scanned data. Deliverable D7.3 details the procedure, measures, and findings of these user evaluation studies. A brief overview of the participants and their subjective feedback is summarised here regarding the therapy modules.

6.2. Participants

Twenty-nine (20 male, 9 female) users (age ranges from 16 – 82, *M=45.07, SD=11.90*) took part in the final evaluation of the PRIME-VR2 bespoke VR controllers at the three living labs. Only in Nicomed Rehabilitation Centre in Cyprus, two controllers were used. Together with a lefthand bespoke controller built based on actual user data, an additional righthand controller was used for the study. Detailed information regarding each participant's demography, background, health conditions, and therapeutic requirements and their subjective feedback is reported in D7.3. Table 10 summarizes the details of the users who volunteered for the PRIME-VR2 bespoke controller evaluation at the three living labs.

Table 10: The participants who tried the bespoke PRIME-VR2 controllers at the three living labs.

User Group	Participants (*N*)	Male (*N*)	Female (*N*)	Age (*Mean*)	Age (*SD*)	Bespoke Controller
Stroke[1]	13	10	3	64.61	10.26	Lefthand, Righthand[4]
Musculo Skeletal Injury[2]	12	8	4	32.83	9.22	Righthand
Dystonia[3]	4	2	2	37.75	16.22	Righthand
	29	**20**	**9**	**45.07**	**11.90**	

[1] Nicomed Rehabilitation Centre, Cyprus.

[2] Saint James Hospital, Malta

[3] GDIH, UK.

[4] Both lefthand (designed with scanned data from a user) and righthand bespoke PRIME-VR2 controllers were used at KNRC.

6.3. Data Collection

In addition to the comfort assessment method developed by Knight et al. [11] mentioned in 5.2 above, three other questionnaires were used during the evaluation study. While the participants' overall experience was assessed using a short version of the standard User Experience Questionnaire (UEQ-S) [15], their sense of presence [16] and embodiment [13] were assessed using two separate questionnaires. Besides, a semi-structured interview was conducted. The details of the data collection and the analysis are reported in D7.4.

6.4. Protocol

The study protocol, including the data collection methods and questionnaire used for each living lab, is discussed in detail in D7.4. In short, a mixed-method approach was followed for the user evaluation study.

6.5. Results

The results from the user evaluation studies conducted separately at three living labs for a period of three weeks are summarised in D7.4. In a nutshell, the results include each user's wearable comfort with the bespoke controllers, their sense of presence and embodiment in the VR, overall user experience of the VR-based rehabilitation, and their subjective feedback on the controller and games.

6.5.1. Users' Feedback

D7.3 presents a detailed report on the feedback from all three user groups. We outline some of the key elements related to the functionality of the therapy modules below.

All users are motivated to use and experience VR for therapeutic purposes. The users with stroke had minimal hand movements, particularly wrist and finger movements. They had a minimal ability to extend their wrist or fingers compared to flexion. The users with stroke were given physical assistance; the therapist helped them lift their arms to see the controller in VR to interact with the game.

Due to the severity of their conditions, the majority of the users with stroke felt that the default resistance of the bespoke controller was very high for most of them. Because of this reason, they were unable to use the controller to perform the interactions even with the default resistance. More importantly, the users with stroke had a very minimal ability to extend their wrists or fingers compared to flexion. Therefore, using the same or similar resistance level for both wrist and finger therapy is not viable, particularly for stroke users. The best solution should be to provide different resistance levels for flexion and extension. Further, the users with stroke mentioned that the bespoke controller, particularly around the wrist part, is heavy and adds additional weight to their hands. Besides, the resistance aspect implemented in the bespoke controller for users with Stroke/MSI is different from conventional therapy as the required resistance is provided using different combination options based on the users' conditions, such as using Velcro straps and wrist bands. In most cases, even the therapists manually provide resistance for the stroke users.

On the other hand, one user with MSI recommended having the customisable resistance, where users could manually set up resistance based on their comfort and preference, depending on the demands of the games.

The therapy module for the bespoke controller for users with Dystonia produced noisy sensor data due to their cramping and tremors. Some even report a complete loss of control following a short session using the controller to perform interactions in VR. For most users with Dystonia, their conditions were a prominent issue during the evaluation study.

6.6. Summary

The main objective of the user evaluation experiment was to explore the performance and acceptability of the bespoke controllers and the VR-HABIT platform to perform upper limb therapeutic exercises. The findings from the user evaluation conducted at three living labs are discussed in detail in D7.3. Regarding the therapy modules, it was learned that the default resistance is still very high for the majority of stroke users. Using/proving the same resistance level is not viable for them. Thus, the users need different resistance levels for wrist flexion and extension.

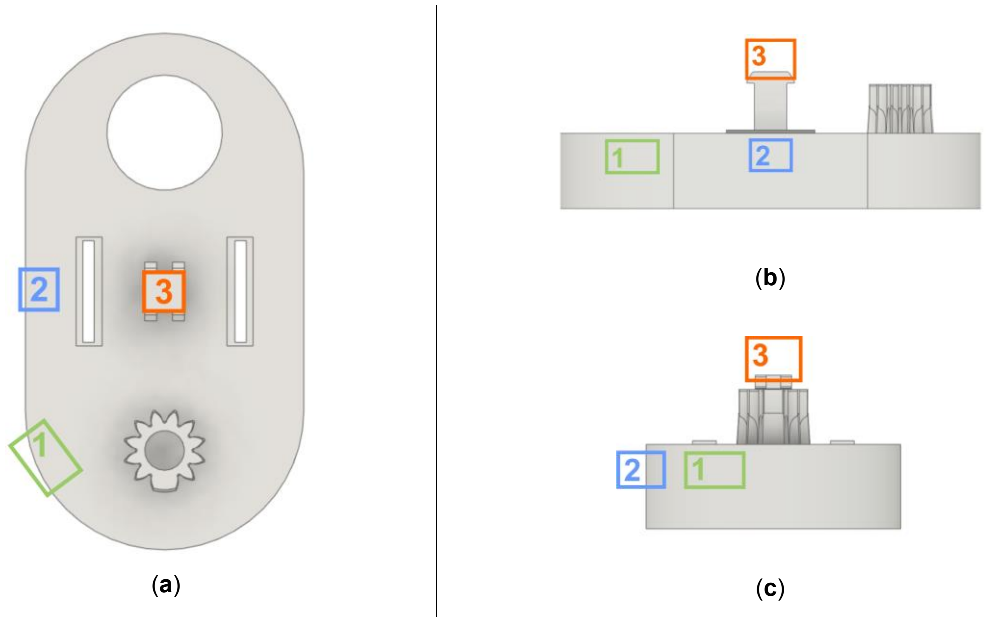
7 *DESIGN RECOMMENDATIONS*

During the user evaluation studies with healthy and actual users and the free-fall test, it was learned that the Pogo pin connections were affected during the change in the resistance level, resulting in a non-functional resistance module. Similar issues were observed when the resistance module accidentally fell down during the studies and also during the simulated free-fall test. Furthermore, the components, including the linear gear and electrical cables tightly packed and interferes with the functionality after each operation. In order to address these issues, two key alternative design recommendations are derived in the following sections:

1. Replace Pogo pins with custom-design USB-C breakout boards.
2. Replace the gear motors with a manual resistance setup.

7.1. Replace Pogo Pins with USB-C Breakout Board

The current design of using the Pogo pins causes two main issues: (1) connection problems during the change of resistance level and (2) the number of cables used to connect the pair of female Pogo pin boards. These issues can be solved by replacing the Pogo pin connections with alternative connectivity options, which will (1) solves the connection issues and (2) also minimise the congestion of the components inside the resistance module. Figure 15 outlines the three potential locations of the proposed redesigns of the custom-designed USB-C breakout boards inside the current design of the resistance module. The merits of these three proposed design adjustments or redesigns are discussed in detail in the following sections.



(**a**)

(**b**)

(**c**)

Figure 15 Illustration of the potential locations of the proposed PRIME-VR2 resistance module adjustment or redesign with three types of custom-designed USB-C breakout boards inside the resistance module: (**a**) top view; (**b**) side view; and (**c**) rear view.

7.1.1. USB-C Breakout Board on the Rear-End of the Resistance Module

This proposed elimination of the Pogo pins method is achieved with a custom-designed USB-C breakout board. The custom-designed USB-C breakout board will replace the two female Pogo pin boards in the resistance module; subsequently, the USB-C breakout board in the wrist module – houses the male Pogo pins. Figure 16 illustrates the proposed USB-C breakout board and the potential placement of the same inside the resistance module.

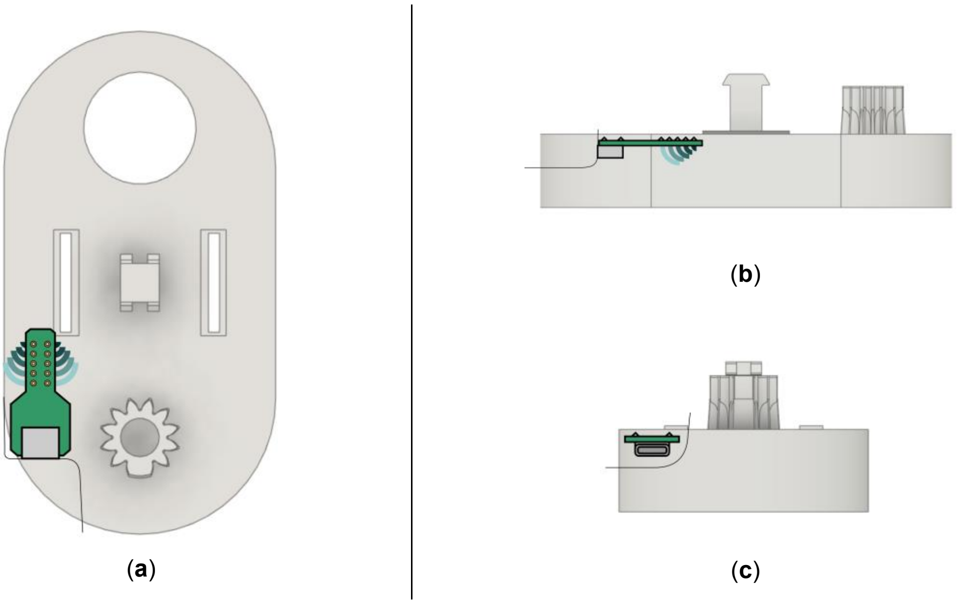
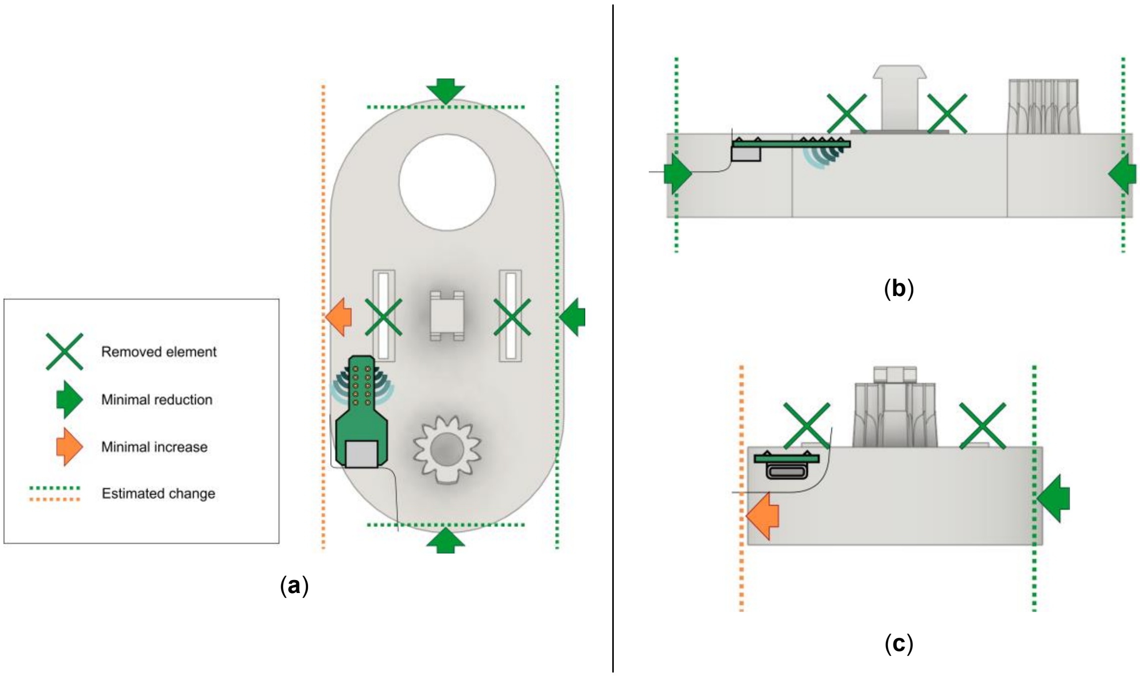

(a)
(b)
(c)

Figure 16 Illustration of the proposed custom-designed USB-C breakout board on the rear side of the resistance module: (**a**) top view; (**b**) side view; and (**c**) rear view.

The advantages of integrating the proposed USB-C breakout board inside the resistance module and the existing components it eliminates are illustrated in Figure 17.



(a)
(b)
(c)

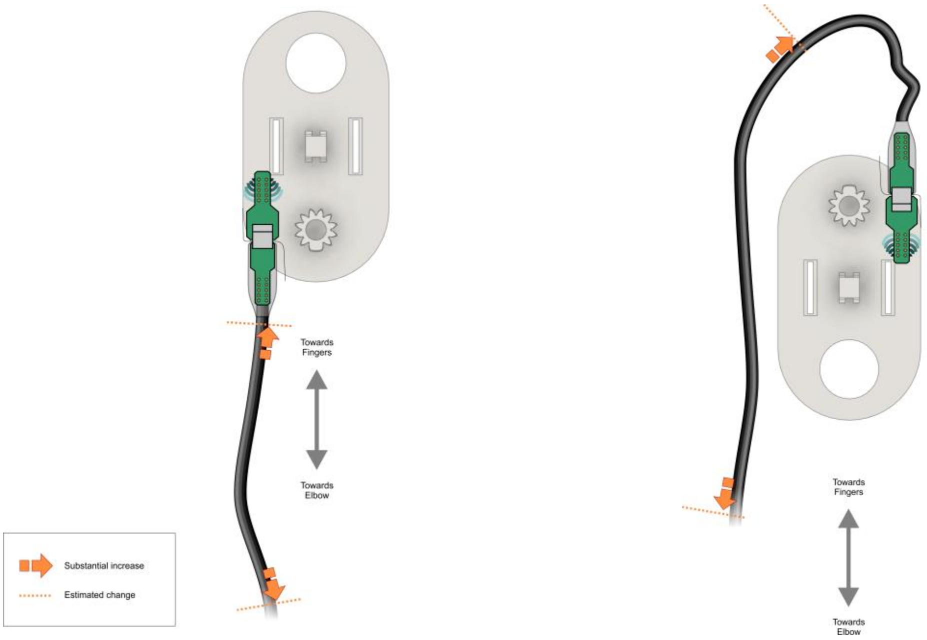
Figure 17 Illustration of how the proposed custom-designed USB-C breakout board inside the resistance module (**a**) eliminates the Pogo pins on both sides; (**b**) subsequently reduces the overall dimension of the resistance module; and (**b**) very minimal increase of the current version to accommodate the proposed board.

Figure 18 illustrates the USB-C connectivity with the proposed USB-C breakout board to the mainboard, which eliminates the current design of the USB-C breakout board on the wrist module.

(a) (b)

Figure 18 Illustration of the USB-C connectivity and the elimination of the USB-C breakout board on the wrist module.

Though this proposed method has several advantages, there is also one important limitation of this design. This USB-C breakout board substantially increases the length of the USB-C cable when the resistance module is switched between the wrist and finger therapy for users with Stroke and MSI (see Figure 19).



(a) (b)

Figure 19 Illustration of the major disadvantage of the proposed design when switched between (a) wrist and (b) finger therapy for users with Stroke and MSI.

Nevertheless, this proposed design is still based on a fulcrum mechanism that utilises a pair of 3D-printed linear actuators, with each actuator comprising a circular gear (the pinion) connected with a custom-designed linear gear (the rack). This approach eliminates the need to use the Pogo pins on both wrist and resistance modules, subsequently minimising the overall dimension of the current design of the resistance module. However, this approach increases the length of the USB-C cable (see Figure 20).

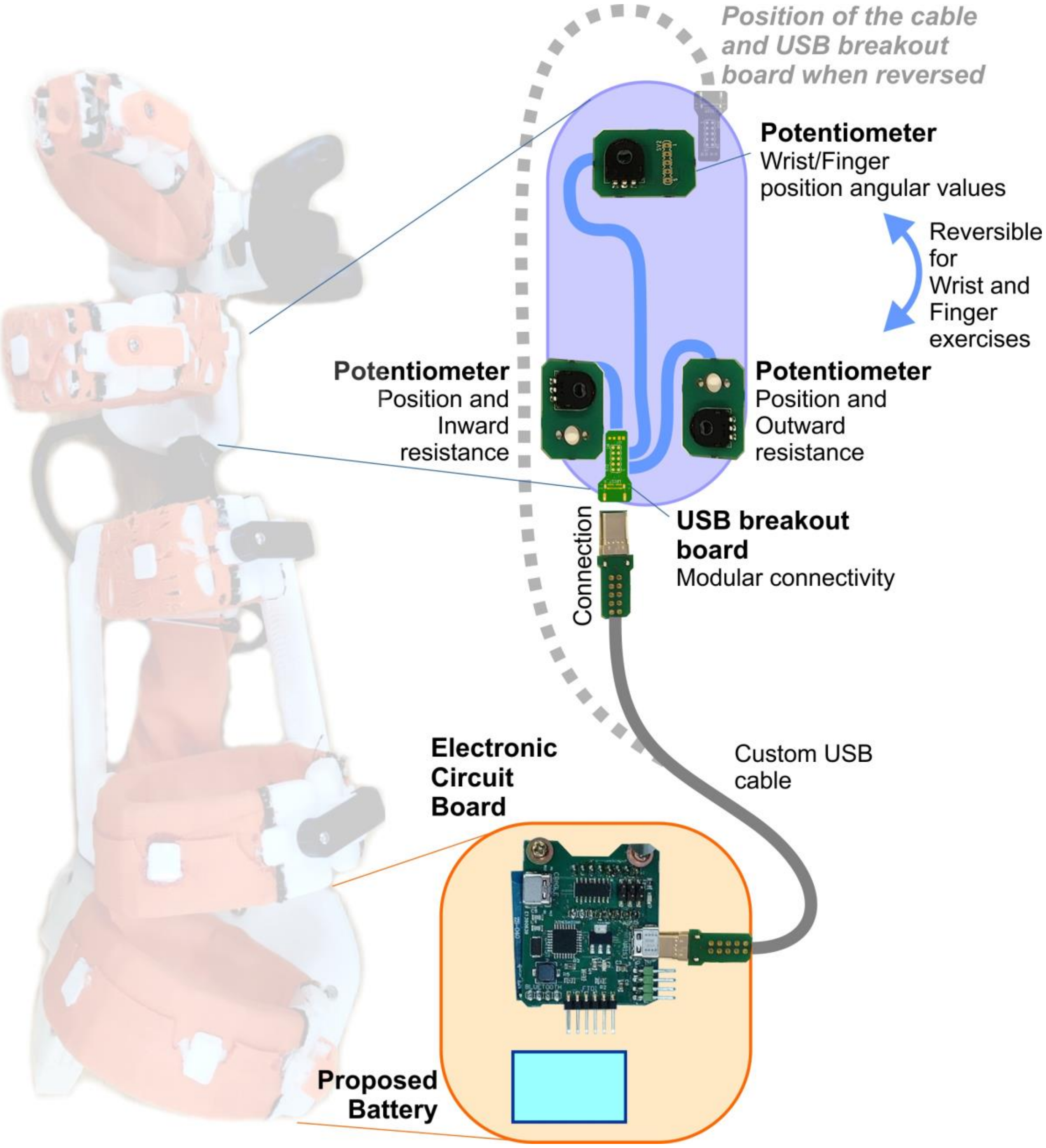


Figure 20 Illustration of the USB-C breakout board on the rear side of the resistance module, other electronic components and their corresponding 3D printed assembly component for the controller of Stroke and MSI users.

7.1.2. USB-C Breakout Board on the Sides of the Resistance Module

The previous approach of placing the custom-designed USB-C breakout board on the rear side of the resistance module increases the length of the USB-C cable, which connects the therapy module with the core module. As the approach eliminates the Pogo pins and the USB-C breakout board on the wrist module, an alternative design of the USB-C breakout board and the placement is considered, as shown in Figure 21. Unlike the previous approach, this approach places a custom-designed USB-C breakout board on the side of the resistance module.

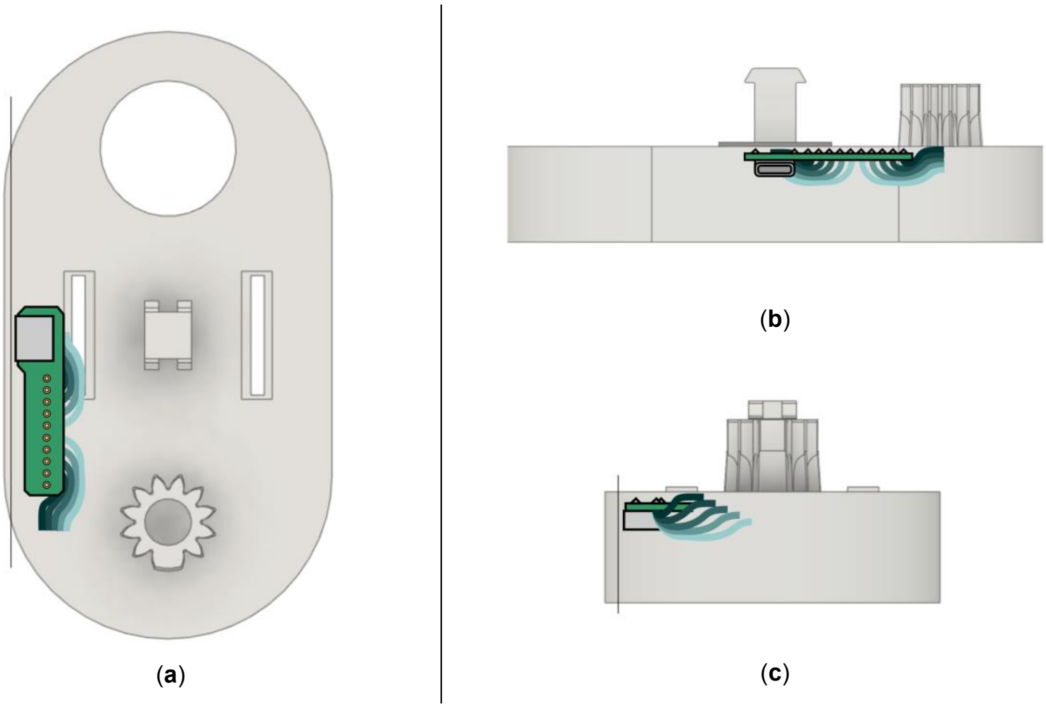
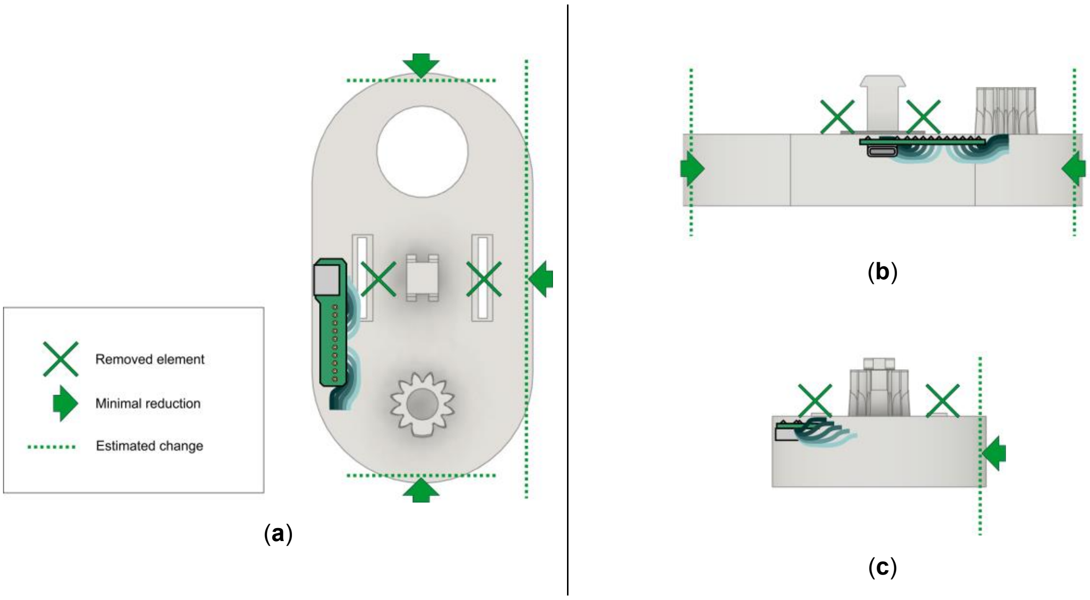

(a)
(b)
(c)

Figure 21 Illustration of the proposed custom-designed USB-C breakout board on the side of the resistance module: (**a**) top view; (**b**) side view; and (**c**) rear view.

As in the previous approach, the proposed custom-designed USB-C breakout board will replace the two female Pogo pin boards in the resistance module; subsequently, the USB-C breakout board in the wrist module – houses the male Pogo pin board (see Figure 22).



(a)
(b)
(c)

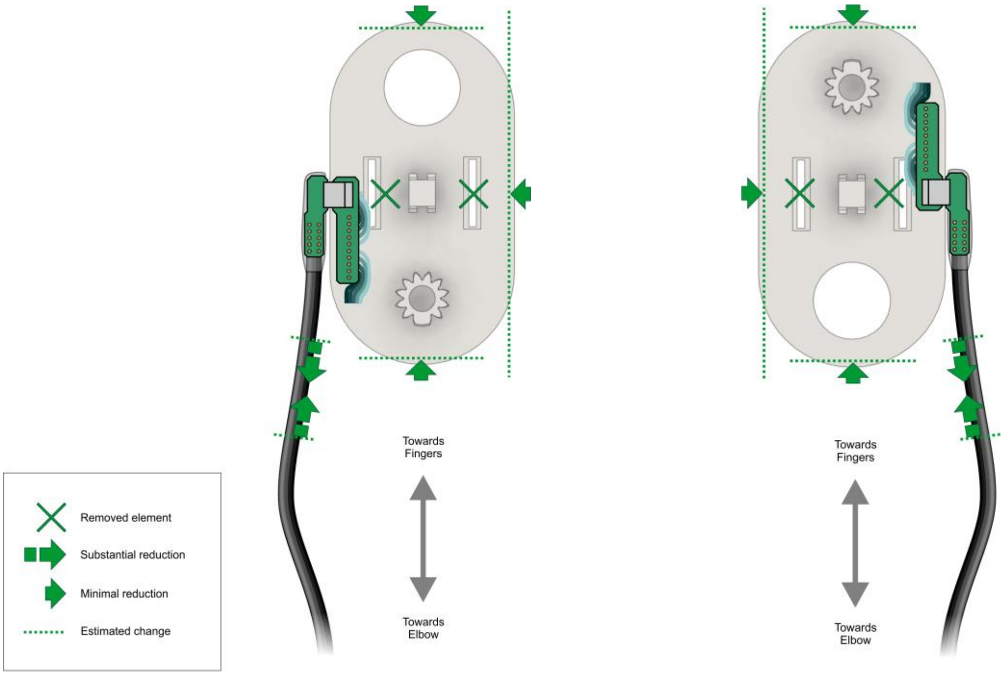
Figure 22 Illustration of how the proposed custom-designed USB-C breakout board inside the resistance module influences the design changes: (**a**) top view; (**b**) side view; and (**c**) rear view.

The USB-C connectivity with the proposed USB-C breakout board to the mainboard, which eliminates the current design of the USB-C breakout board on the wrist module, is achieved similarly to the previous method. Figure 23 illustrates this method below.

(**a**) (**b**)

Figure 23 The USB-C connectivity is achieved by eliminating the current USB-C breakout board on the wrist module.

Unlike the previous method, this design of the USB-C breakout and the placement of the same on the side of the resistance module substantially decreases the length of the USB-C cable when the resistance module is switched between the wrist and finger therapy for users with Stroke and MSI (see Figure 24).



(**a**) (**b**)

Figure 24 Illustration of how this design approach significantly decreases the length of the USB-C when switched between (a) wrist and (b) finger therapy for users with Stroke and MSI.

The second design is also based on a fulcrum mechanism that utilises a pair of 3D-printed linear actuators, with each actuator comprising a circular gear (the pinion) connected with a custom-designed linear gear (the rack). Like the previous method, this approach also eliminates the need to use the Pogo pins on both wrist and resistance modules, subsequently minimising the overall dimension of the current design of the resistance module. Moreover, this approach also minimises the length of the USB-C cable when switched between wrist and finger therapies. However, these two approaches have the USB-C cable on the sides of the resistance, which demands the user to remove and plug the USB-C whenever the resistance module is used for different therapies (see Figure 25).

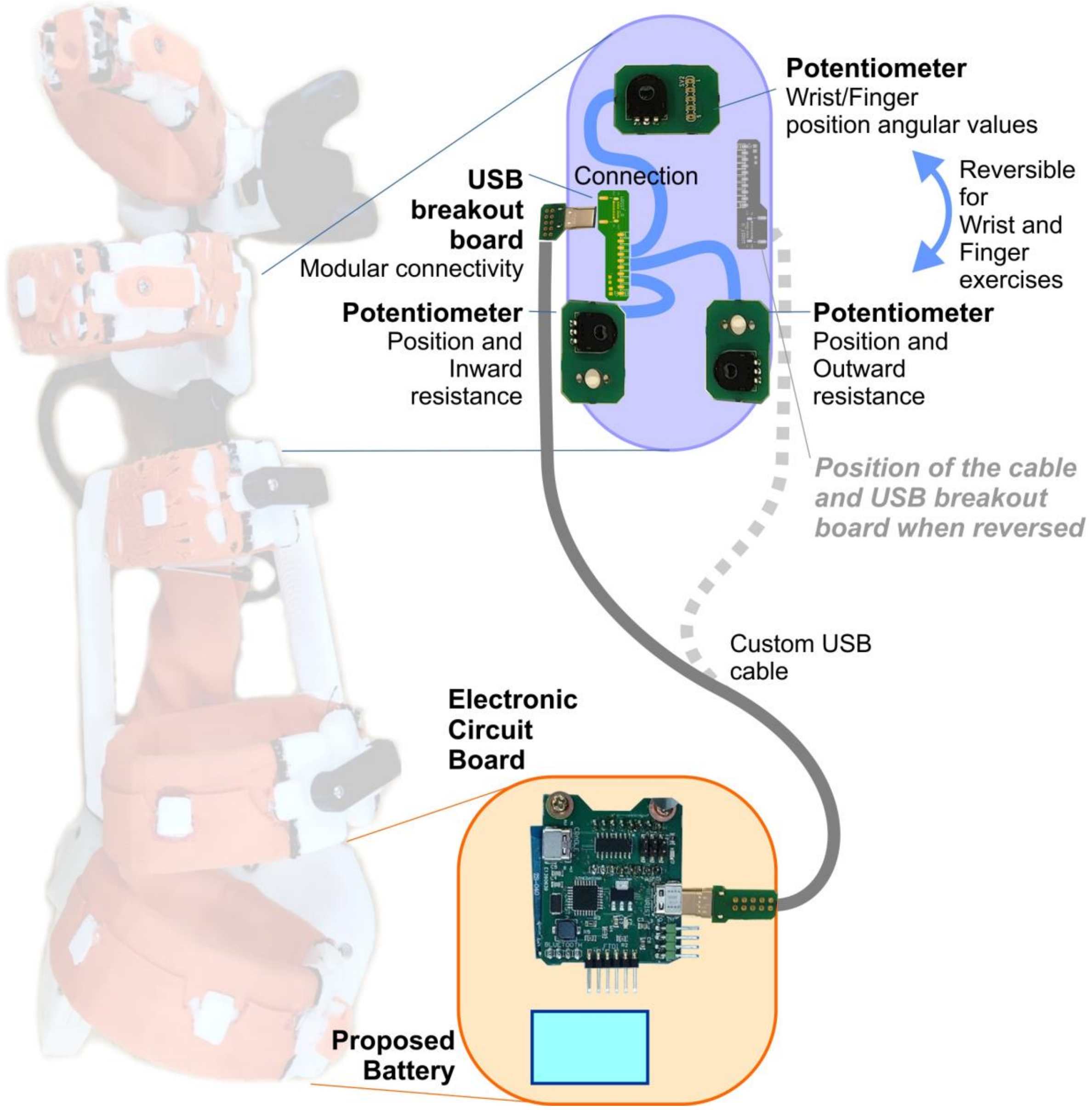


Figure 25 Illustration of the USB-C breakout board on the side of the resistance module, other electronic components and their corresponding 3D printed assembly component for the controller of Stroke and MSI users.

7.1.3. USB-C Breakout Boards inside the Latch Hook of the Resistance Module

The two previous approaches of placing the custom-designed USB-C breakout board inside the resistance module eliminates the Pogo pins and the USB-C breakout board on the wrist module. However, these two approaches still demand the user (or clinicians/therapists) to remove and plug the USB-C cable from the core module whenever the resistance module is switched between the wrist and finger therapies for users with Stroke/MSI. The third proposed approach overcomes the limitations of the previous methods. In this proposed approach, a custom-designed USB-C breakout board is inside the latch hook of the resistance module. Figure 26 illustrates this approach with a custom-designed USB-C breakout board.

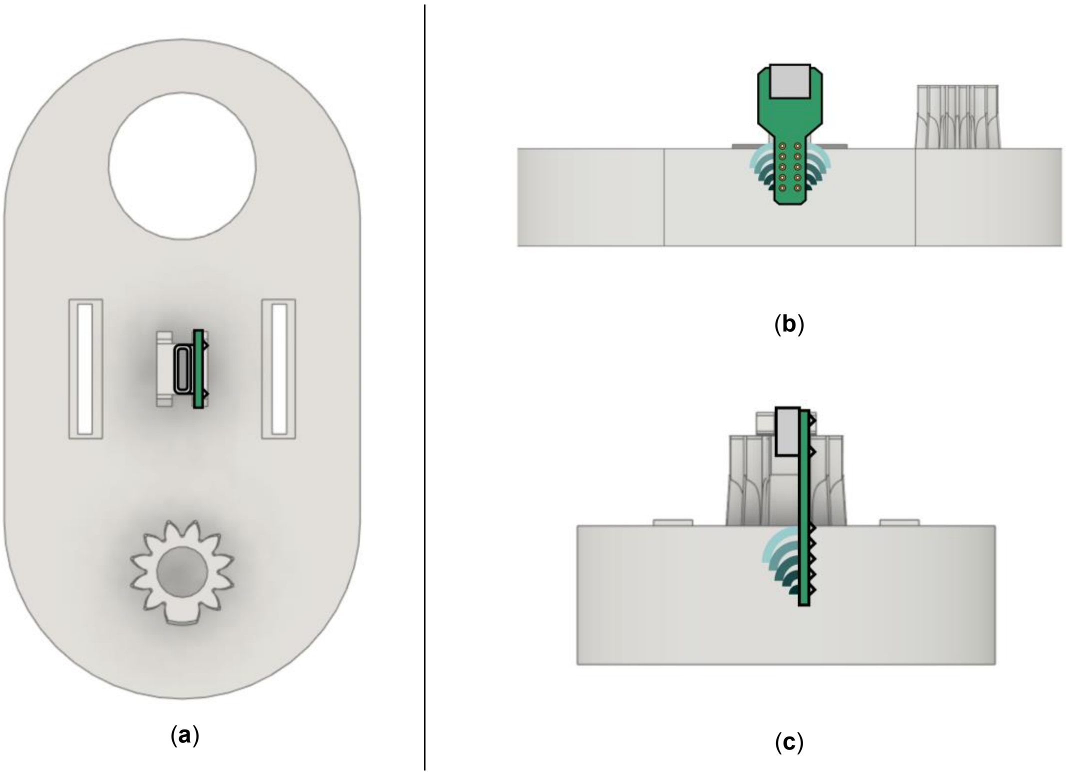
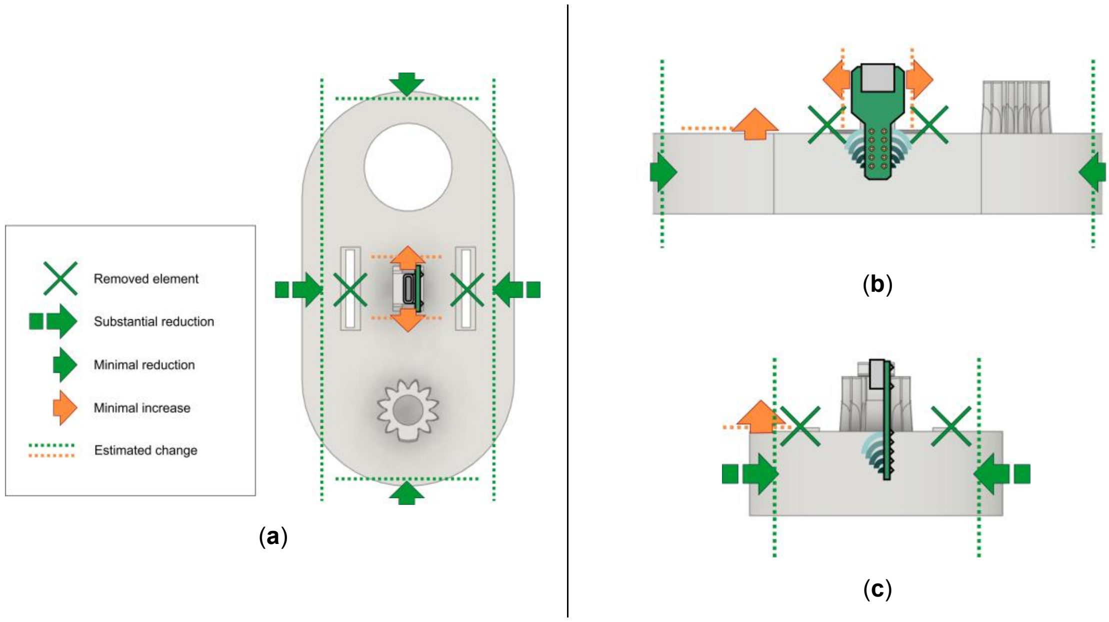

(**a**) (**b**) (**c**)

Figure 26 Illustration of the proposed custom-designed USB-C breakout board inside the latch hook of the resistance module: (**a**) top view; (**b**) side view; and (**c**) rear view.

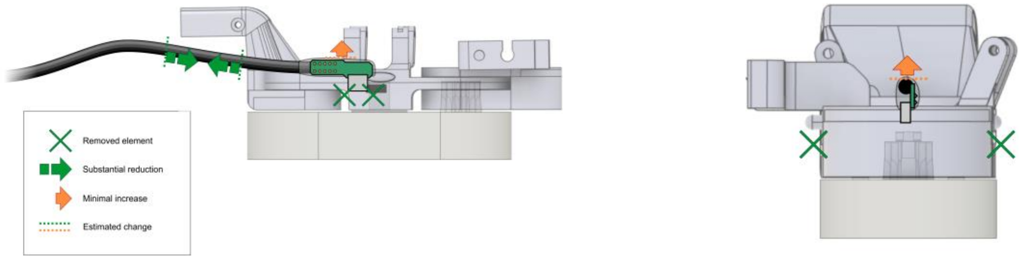
As in the previous two approaches, the proposed custom-designed USB-C breakout board will replace the two female Pogo pin boards in the resistance module; subsequently, the USB-C breakout board in the wrist module – houses the male Pogo pins. Furthermore, unlike the other two methods, this approach can significantly reduce the dimension of the resistance module. Of course, this method requires redesigning the existing latch hook by slightly increasing its dimension (see Figure 27).



(**a**) (**b**) (**c**)

Figure 27 Illustration of the benefits of the proposed custom-designed USB-C breakout board design inside the latch hook of the resistance module : (**a**) top view; (**b**) side view; and (**c**) rear view.

The USB-C breakout board inside the latch hook of the resistance module hides the USB-C cable connectivity. Thus, the USB-C cable will not be visible around the therapy module, and there is no need to plug/unplug the cable when switching between the wrist and finger therapies, and vice versa. This advantage means that the length of the USB-C cable can be substantially reduced. However, the current wrist module needs modifications to accommodate this method. Figure 28 demonstrates how the USB-C cable flows through the wrist module to the resistance module.



(**a**) (**b**)

Figure 28 Illustration of how this design approach (**a**) hides the USB-C cable within the therapy module, thus significantly (**b**) reducing the length of the cable.

Like the previous approaches, the third method is also based on a fulcrum mechanism that utilises a pair of 3D-printed linear actuators, with each actuator comprising a circular gear (the pinion) connected with a custom-designed linear gear (the rack). Like the previous two methods, this approach also eliminates the need to use the Pogo pins on both wrist and resistance modules, subsequently minimising the overall dimension of the current design of the resistance module. Moreover, this approach also seamlessly hides the USB-C around the therapy module, thus significantly minimising the length of the USB-C, making switching between wrist and finger therapies easier and simpler. This approach requires a design change to the wrist, resistance module and particularly the latch hook locking mechanism (see Figure 29).

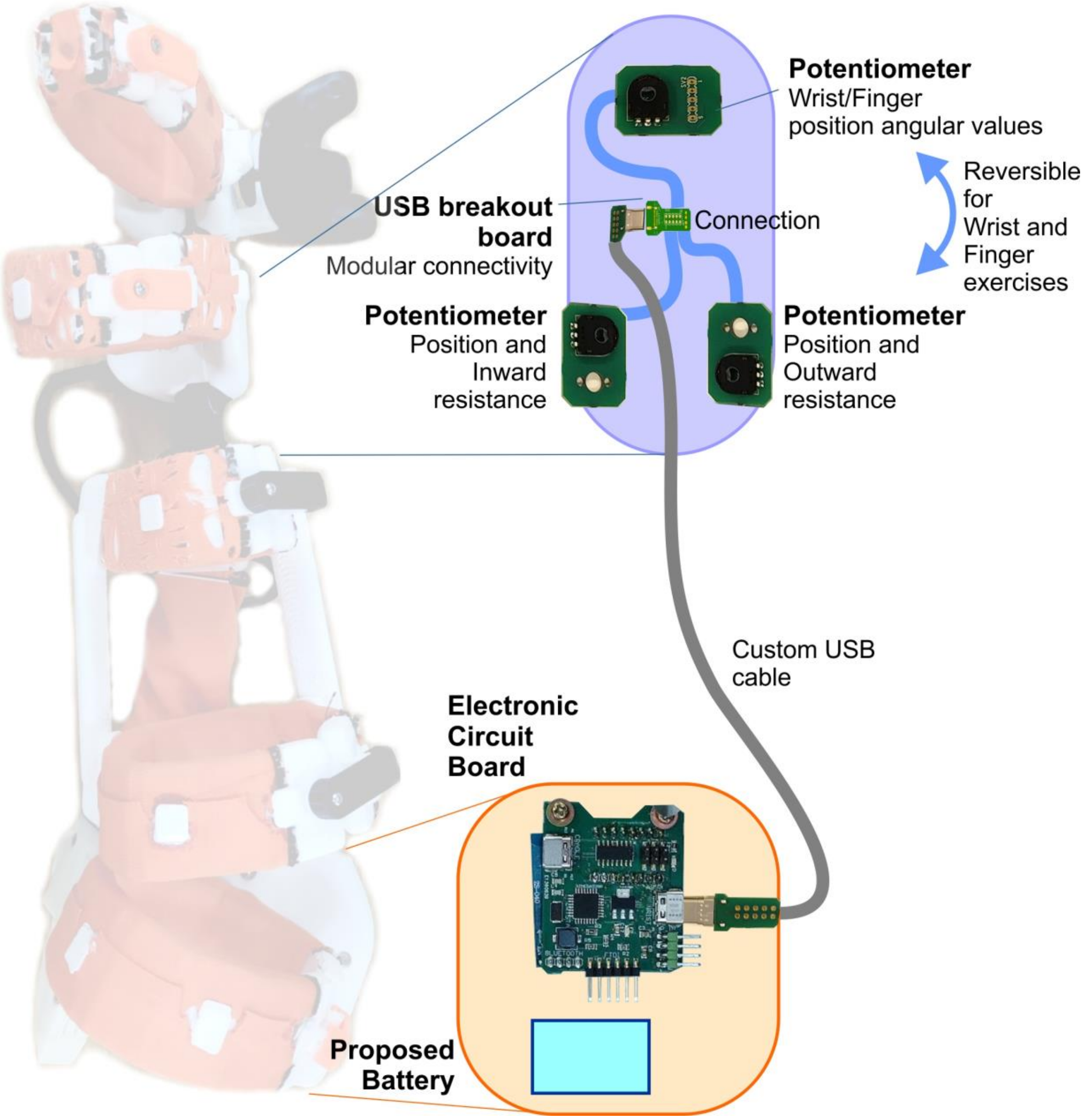
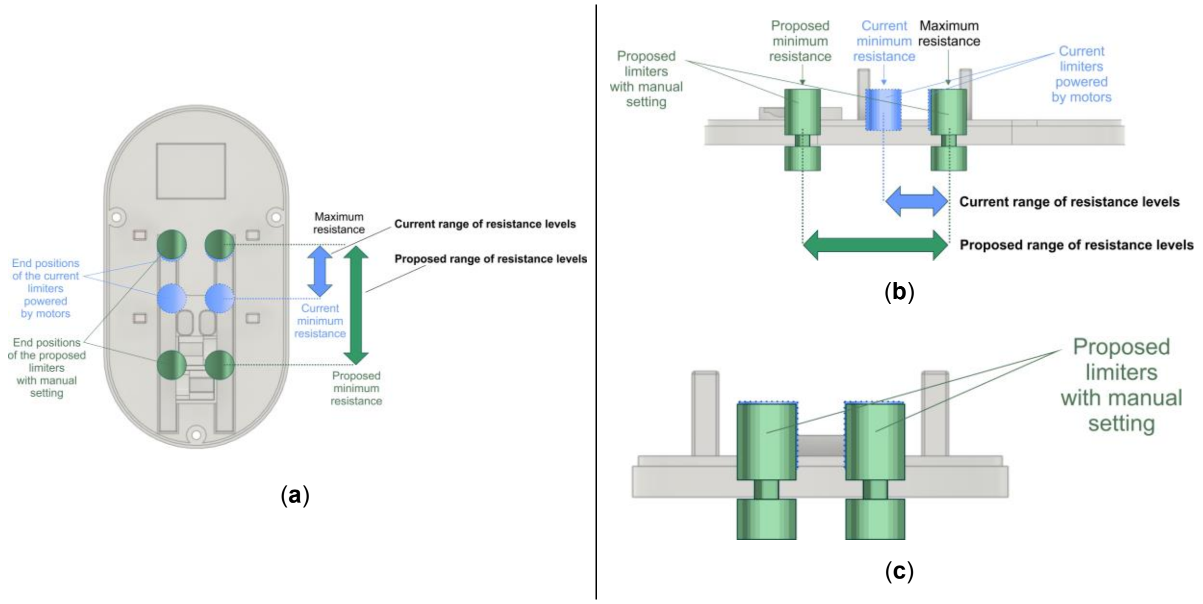


Figure 29 Illustration of the USB-C breakout board inside the latch hook of the resistance module, other electronic components and their corresponding 3D printed assembly component for the controller of Stroke and MSI users.

The above three approaches successfully eliminate the Pogo pins by introducing USB-C breakout boards to solve the issues observed with the Pogo connectivity during the user evaluation studies. However, all these changes still utilise a fulcrum mechanism that utilises a pair of 3D-printed linear actuators, with each actuator comprising a circular gear (the pinion) connected with a custom-designed linear gear (the rack). As highlighted in deliverable D4.4, a significant impact of the drop test was the failure of the custom-designed linear gear mechanism, particularly the damaged circular gears resulting in a resistance module non-functional. In addition, it was also learned during the user studies that both the default and different levels of resistance provided by this mechanism were very high for the actual users, particularly the users with stroke. Therapists also highly recommend allowing the users to change the resistance manually with very minimal gradual increments in the resistance, like in the conventional therapy. The following method is proposed to address these concerns with the mechanism, which replaces the motors, thus eliminating the circular gears (the pinions) in the resistance module.

7.2. Replace the Gear Motors with Manual Resistance Setup

The proposed method replaces how the two standard low-power micro metal gear motors are used to rotate the pinions, which causes the rack to be driven/moved in a line. Thus, it eliminates the need for a pair of circular gears (the pinion) connected with a custom-designed linear gear (the rack). As an alternative option, the change of resistance level can be done manually, for instance, using a spring mechanism instead of the gear motors. This approach allows the users to manually change to their preferred and comfortable resistance level by themselves from the bottom of the resistance module. This method can be achieved differently for both wrist and finger exercises and can be done simultaneously without having to remove the controller or through the PC. Figure 30 illustrates the proposed options and their functions in detail.



(**a**)

(**b**)

(**c**)

Figure 30 Illustration of the proposed manual resistance setup method, which eliminates the motors, potentiometers, and circular gears: (**a**) top view; (**b**) side view; and (**c**) manual resistance setting option.

As this approach eliminates the need for low-power micro metal gear motors and introduces the manual resistance setup method, the removal of the motor and potentiometer PCBs and the cables connecting these boards with the boards will increase the space inside the resistance module. Thus, the resistance mechanism will always be functional, and the manual setup can allow the users to choose their preferred/comfort level of resistance during the exercise without/with minimum assistance from the therapists/others.

Moreover, the removal of the motors will enable the processing unit not to have the dedicated dual multiplexer (2x4), dual H bridge motor driver IC and local 5v Regulator. Thus, the processing unit can only have an ATmega328p microprocessor and a Bluetooth Low Energy (BLE) module, which significantly reduces the dimension of the board, and the power supply.

Nevertheless, this approach retains other components, such as the racks, needle roller bearings, deep groove ball bearing connected with a thin 360-degree rotary potentiometer, and the USB-C breakout board inside the latch hook part of the resistance module. The rotating spine measures the angle when the user performs therapeutic wrist/finger flexion or extension exercises. Analog readings from the potentiometer are transmitted to a microprocessor in the core module through the custom-developed USB-C cable. Figure 31 illustrates this approach in detail with the components and their corresponding 3D printed assembly component for the controller of Stroke and MSI users. In this design, the total weight of all the electronic boards, potentiometers, cables, and the battery can be as low as around 30-40g.

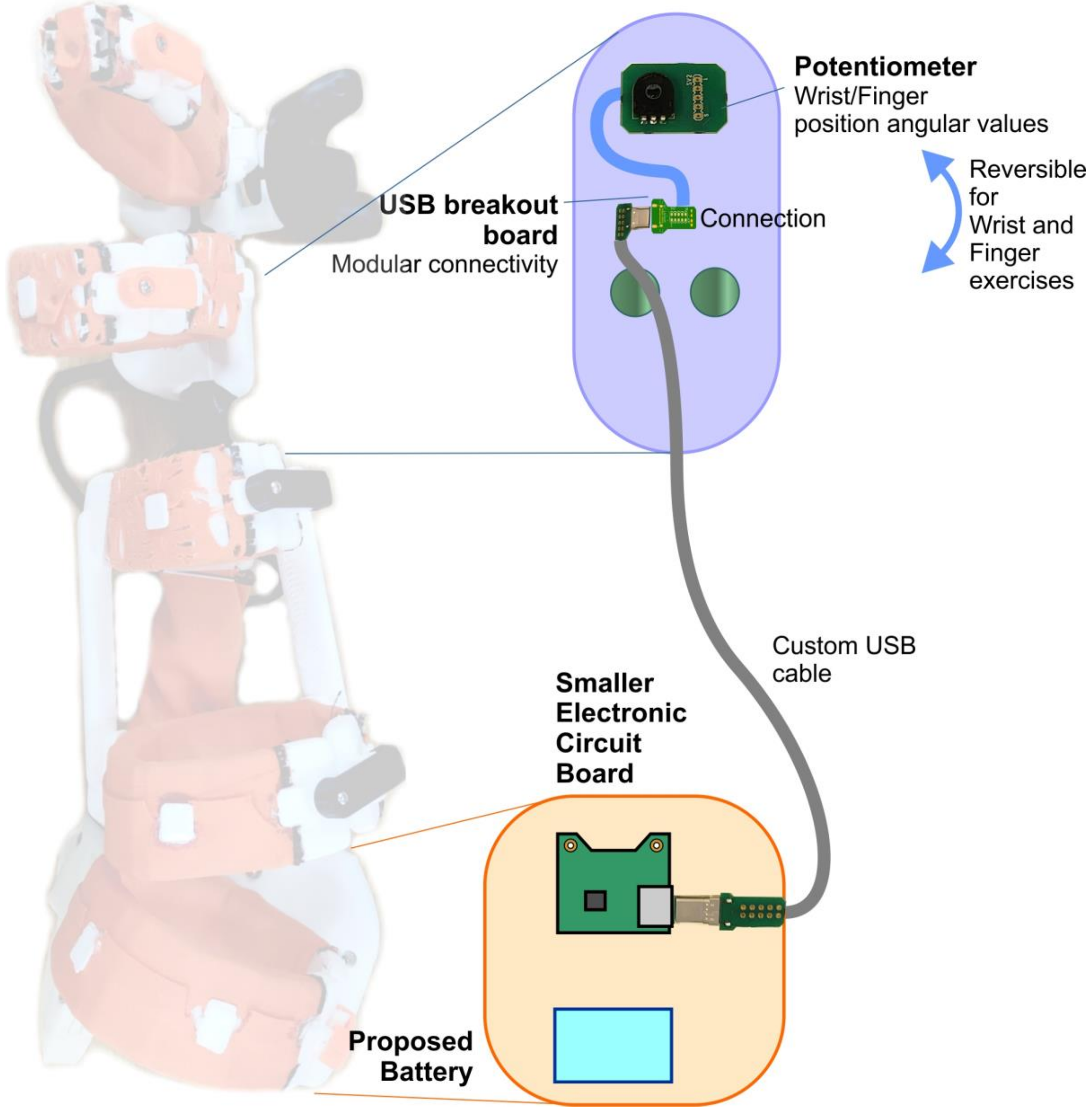


Figure 31 Illustration of the electronics components and their corresponding 3D printed assembly component for the controller of Stroke and MSI users.

8 CONCLUSION

In this public deliverable of the PRIME-VR2 project, we presented the bespoke VR controllers, their working principles of the therapeutic modules, and findings from a series of user evaluation studies from healthy, frequent VR users and actual novice users. The design of the user evaluation study with healthy users resulted from task 5.6 of the PRIME-VR2 project. The main focus of the T5.6 was to ensure the hardware and software performance of the design and functional aspects of the bespoke controllers. In Section 3, we summarised the design and working principle of the two therapy modules, the custom-designed and developed electronics components, including the mainboard and other boards, and the electronic components for the two bespoke VR controllers. The electronics for the bespoke controller for Stroke, MSI, and Dystonia users consists of two types of boards (mainboard and USB-C breakout board) connected via a custom-designed USB cable. All these boards are designed, manufactured, and assembled at the FabLab and other facilities at the University of Oulu. The processing units of the PRIME-VR2 controllers consist of an ATmega328p microprocessor. In addition, the mainboard also includes a dual multiplexer (2x4), dual H bridge motor driver IC, local 5v Regulator, Bluetooth (HC-05), USB C breakout board and a battery connector. The total weight of all the electronic boards, potentiometers, cables, and excluding the rechargeable battery and the pair of micro metal gear motors for the controller for users with stroke, is around 51g. At the same time, the electronic components used for the controller for Dystonia users are under 40g.

The developed bespoke controllers were evaluated with healthy adults who are also frequent VR users. In addition to 29 actual users, twelve frequent VR users, who are also university students, were recruited to validate the performance of the PRIME-VR2 bespoke controllers for upper limb therapeutic exercises. Their interaction experience using the bespoke VR controllers in terms of usability, wearable comfort, and subjective rating of the PRIME-VR2 controllers on ease of use to perform the therapeutic exercises was summarised in Section 5. In addition, we also briefly outlined the user feedback from three living labs.

Finally, in Section 7, we concluded the deliverable by incorporating the recommendations for the design and functionality of the bespoke controllers from a wide range of users.

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10 APPENDIX

The following are the questionnaires/descriptions used in the data collection for the user experiments in addition to the general demographic and background questions.

10.1. Comfort Rating Scale

- I am worried about how I look when I wear the controller.
- I feel tense or on edge because I am wearing the controller.
- I can feel the controller on my body.
- I can feel the controller is moving.
- The controller is causing me some harm.
- The controller is painful to wear.
- Wearing the controller makes me feel physically different.
- I feel strange wearing the controller.
- The controller affects the way I move.
- The controller inhibits or restricts my movement.
- I do not feel secure wearing the controller.

10.2. System Usability Scale

- I think that I would like to use this controller frequently.
- I found that the controller unnecessarily complex.
- I thought that the controller was easy to use.
- I think that I would need the support of a technical person to be able to use the controller.
- I found the various functions in the controller were well integrated.
- I thought there was too much inconsistency in the controller.
- I would imagine that most people would learn to use the controller very quickly.
- I found the controller cumbersome to use.
- I felt very confident using the controller.

- I needed to learn a lot of things before I could get going with the controller.