A Pneumatic HandHeld Device for Finger Active Tele-Rehabilitation

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Abstract. The objective of this paper is the development of a handheld, untethered device for active finger tele-rehabilitation. The device has the capacity to measure both hand and finger motion, and to provide multimodal haptic feedback on each user's finger. The paper will present the system functional design, inspired by the recent trend and requirements for haptic devices. The final part of the paper will discuss the early prototyping of the system, addressing both hardware and software aspects aimed at utilizing the device both as a tool for rehabilitation and for collecting data to objectively quantify the rehabilitation status.

Keywords: Finger Rehabilitation · Haptics · Soft Robotics · Pneumatics

1 Introduction

Tele-rehabilitation practices refer to methods that enable the functional recovery of a limb following an injury without requiring visits to medical or hospital centers. Tele-rehabilitation has garnered significant interest in recent years, as recent reports from the World Health Organization (WHO) highlight an unmet need for devices to assist physiotherapists in conducting and monitoring rehabilitation practices [1]. This demand is further supported by the WHO Global Disability Action Plan, which emphasizes a commitment to allocating adequate financial resources for providing appropriate rehabilitation services and assistive technologies.

Rehabilitation devices are typically classified according to the limb they target and the type of device, such as end-effector systems [5], exoskeletons [3], wearables [7], etc. Regarding the development of devices for hand rehabilitation, the practical implementation of inventions in clinical contexts often faces challenges. Specifically, the design choice of having a number of independent systems for each individual measurement or actuation often results in excessive weight and bulk, making them difficult to manage [6]. This leads to an unavoidable trade-off, at the design stage, between creating a highly functional system and developing a compact, user-friendly device.

This paper introduces a pneumatic and lightweight haptic device, named PAL-HAND.Q [2], which is based on the following design requirements derived from scientific literature [6,9]:

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- capability to measure and track the motion of the hand holding the device;
- capability to track finger motion;
- ability to provide multimodal haptic feedback, i.e., combining signals of different types, such as force, vibration, and so on;
- adaptability of the device's geometry to accommodate various anthropometric dimensions of the hand;
- development of a low-energy consumption system that is untethered and portable.

The next section will outline the concept and design of the device, while the rest of the paper will focus on its application in tele-rehabilitation contexts.

2 Concept and Design

The conception of PAL-HAND.Q was driven by the objective of developing a single device capable of facilitating remote finger rehabilitation practices and providing objective quantification of rehabilitation progress. These activities are conducted within an Extended Reality environment, with the intention of enhancing and facilitating physical and cognitive engagement of the user. Figure 1 resumes the application contexts and functionalities of the device, while Fig. 2 depicts its functional schematic.

As can be seen, the device is of the handheld type, designed to be gripped by the user with a single hand. It is composed of a rigid case, on which five deformable membranes are positioned. PAL-HAND.Q is held through contact between the rigid case and the user's palm, along with contact between the fingertips and the deformable bladders. The unit element of PAL-HAND.Q is thus a Soft Pneumatic Sensing Chamber (SPSC) [8]. This SPSC is connected to a closed electro-pneumatic system that acts as a pneumatic spring; i.e., the pressure inside the SPSC increases when the user squeezes it, and consequently, the contact force between the finger and the SPSC also increases. This results in

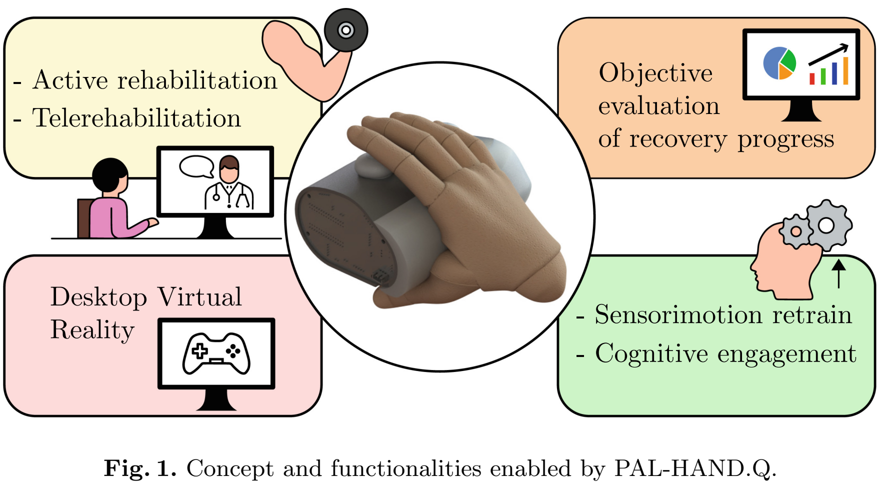


Fig. 1. Concept and functionalities enabled by PAL-HAND.Q.

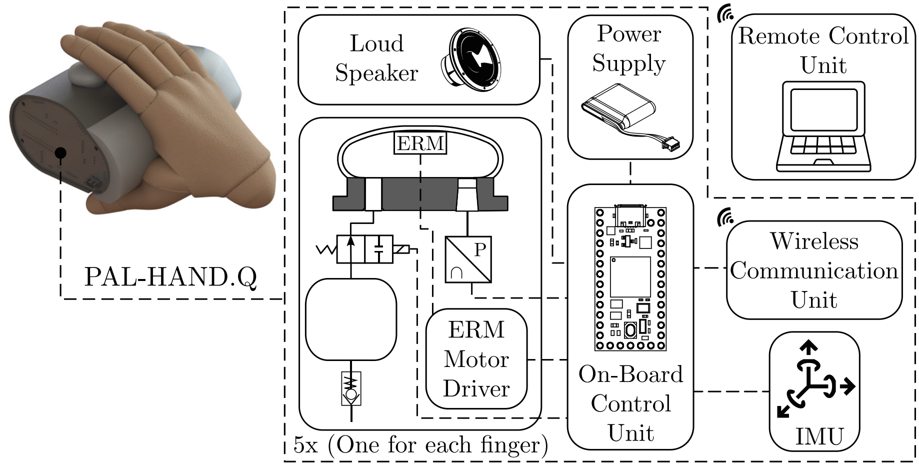


Fig. 2. Functional architecture of PAL-HAND.Q. All components necessary for the device's functioning are within a rigid case that the user can grasp. The device is connected wirelessly to a Remote Control Unit for data monitoring and display.

a kinesthetic feedback that monotonically increases as a function of the amount of SPSC compression.

The circuit is pressurized by connecting the pressure source to a check valve. Therefore, if leakage-free, PAL-HAND.Q does not require a connection to the pressure source during use, but only during its initial setup.

A directional valve is positioned between the SPSC internal chamber and an auxiliary reservoir. When closed, the amount of air that is compressed is lower, resulting in a higher stiffness of the air spring. This valve is primarily included to allow the user to perceive a higher stiffness in response to specific inputs from the control unit. For instance, in the case of a pick-and-place routine in virtual reality, the high stiffness level simulates the contact with the grasped object. In addition to this adjustable kinesthetic feedback between two discrete levels, a vibrotactile haptic feedback is provided to the user by means of an eccentric rotating mass (ERM) vibrating motor. The ERM is positioned within the SPSC chamber, thereby providing localized vibration feedback to the fingertip, since the SPSC prevents vibrations from propagating to the rigid case.

A pressure sensor allows the measurement of the SPSC internal pressure, i.e., it enables tracking the finger motion within the SPSC range of motion. An on-board control unit manages the input/output communications between the SPSC and the auxiliary elements of the device. Among these, an Inertial Measurement Unit (IMU) tracks hand motion, and a loudspeaker provides audio feedback. Finally, a wireless communication unit ensures bi-directional communication with a remote control unit. Therefore, PAL-HAND.Q functions completely untethered, offering the user full freedom of movement.

Figure 3 shows the early prototype resulting from PAL-HAND.Q, manufactured using fused deposition modeling (FDM) methods. PAL-HAND.Q's case is made of rigid plastic material (PLA), while the SPSCs are made of thermoplastic

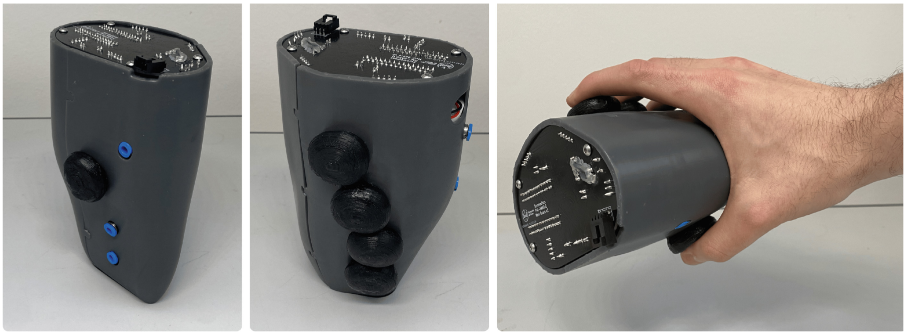


Fig. 3. The PAL-HAND.Q early prototype.

polyurethane (TPU) with a Shore hardness of 60A. The figure also shows the blue-colored check valves, positioned to allow external access without opening the case. The prototype has dimensions of 160 x 120 x 100 mm and a mass of 300 g (without the battery). The setup pressure ranges from 20 to 50 kPa (gauge), and within this range, the pneumatic subsystems are completely leak-free. The range of motion allowed to each finger by the SPSCs is 10 mm, i.e. heach finger can squeeze the SPSC with a maximum stroke of 10 mm. On the upper side of the device, a printed circuit board manages the input/output signals. It should be noted that the prototype places all the necessary components outlined in Fig. 2 within the volume defined by the palm and fingers, with an unavoidable lower constraint on the size of PAL-HAND.Q. Figure 4 shows the resulting shape can be grasped by the hand od a male user with an handspan of 22 cm and a palm length of 10 cm.

3 Applications

To showcase and demonstrate the capabilities of PAL-HAND.Q in tele-rehabilitation contexts, two application examples have been developed and are detailed below. Among these is the use of signals from IMUs and SPSCs to map hand motion in virtual environments, as shown in Fig. 4, where the sequential pressing of four fingers, from index to pinky, is graphically represented. This has been achieved by a wireless communication between PAL-HAND.Q and the remote control unit, while the graphic engine has been developed in Python by using ModernGL and Pygame modules.

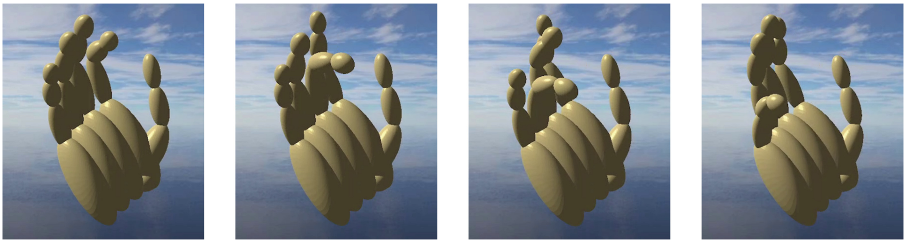


Fig. 4. Sequential pressing of the four fingers, detected by PAL-HAND.Q.

3.1 Memory Game

The simplest form of rehabilitation exercises involves the user repeatedly squeezing the membranes. However, the squeezing sequence can be guided by the control unit, which operates both the ERM vibration motor and the loudspeaker. The input from the control unit is encoded into a vibro-acoustic melody that the user hears, with different notes assigned to each finger. The user's reproduction of the sequence, performed by squeezing the SPSCs, can occur either in real-time or after a delay. In the delayed mode, the user is required to memorize and subsequently reproduce the melody. This mode is referred to as the *memory game*, and its structure is summarized in Fig. 5.

During the initial stages of the routine, the user can set the duration of the melody, the fingers involved, and the stiffness level of each SPSC. User commands are provided exclusively through interaction with PAL-HAND.Q, while commands from the remote control unit are displayed on screen. Figure 6 shows the results achievable at the end of the memory game routine for two different stiffness levels and for two fingers (index and middle fingers). The red dashed line represents the vibration input, normalized with respect to the maximum vibration intensity, while the blue line shows the measured pressure variation. For this demo, the input intensity, that is, the audio and vibration levels, is fixed

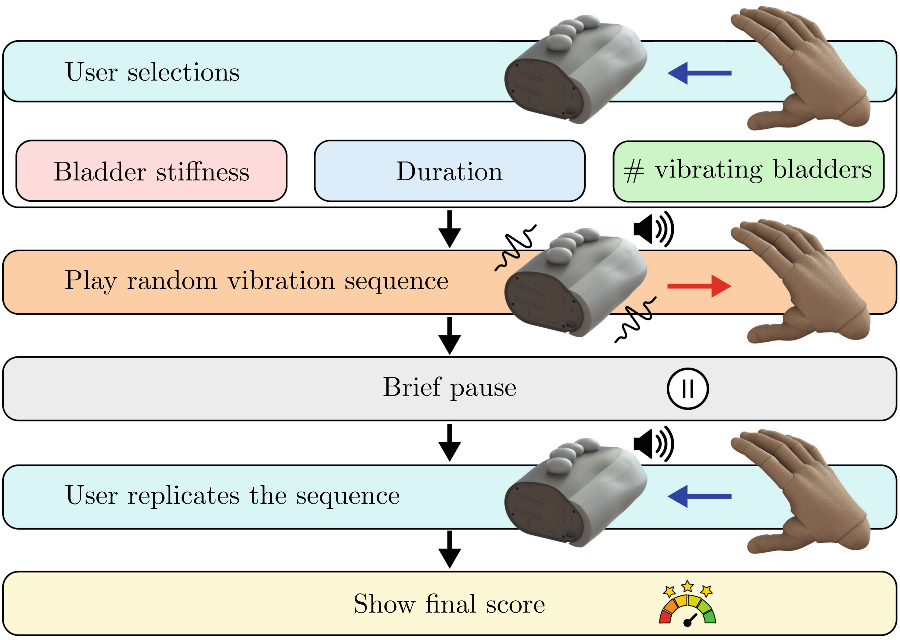
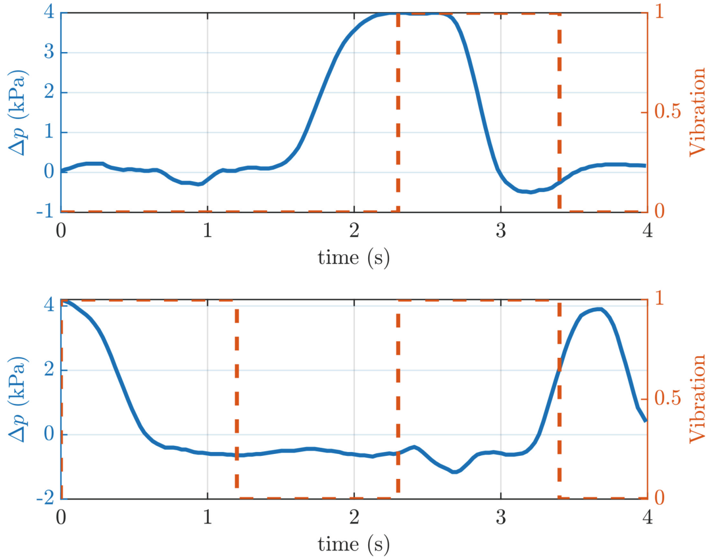
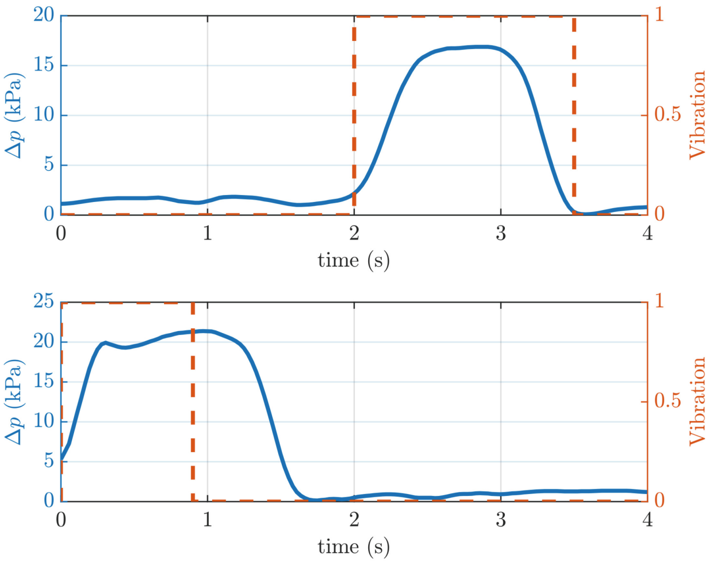


Fig. 5. Block scheme showing the organization of the proposed memory game. The interaction between the user and the device is bidirectional, i.e. there is an exchange of signals coming from and going towards the device, and multimodal (vibrotactile, acoustic and kinesthetic feedback).



(a)



(b)

Fig. 6. Results obtained from the memory game. The set-up pressure is 20 kPa (gauge). **(a)** Valves open (low stiffness). **(b)** Valves closed (high stiffness).

throughout the entire routine; however, this represents an additional difficulty level that can be adjusted.

3.2 Peg-in-Hole Game

Extended Reality (XR) is among the most commonly used technologies to enhance user engagement during rehabilitation practices. XR refers both to the creation of a virtual world (Virtual Reality, VR) and the combination of the real world with virtual additions (Augmented Reality, AR).

As previously mentioned, the use of XR in rehabilitation practices with PAL-HAND.Q is primarily envisioned through peg-in-hole games or similar activities, in which the patient is required to virtually grasp and move objects. The IMU and SPSCs are therefore used to track the motion of the hands and fingers, as shown in Fig. 7, while the switching of directional valves provides the user with the sensation of getting in touch with the object.

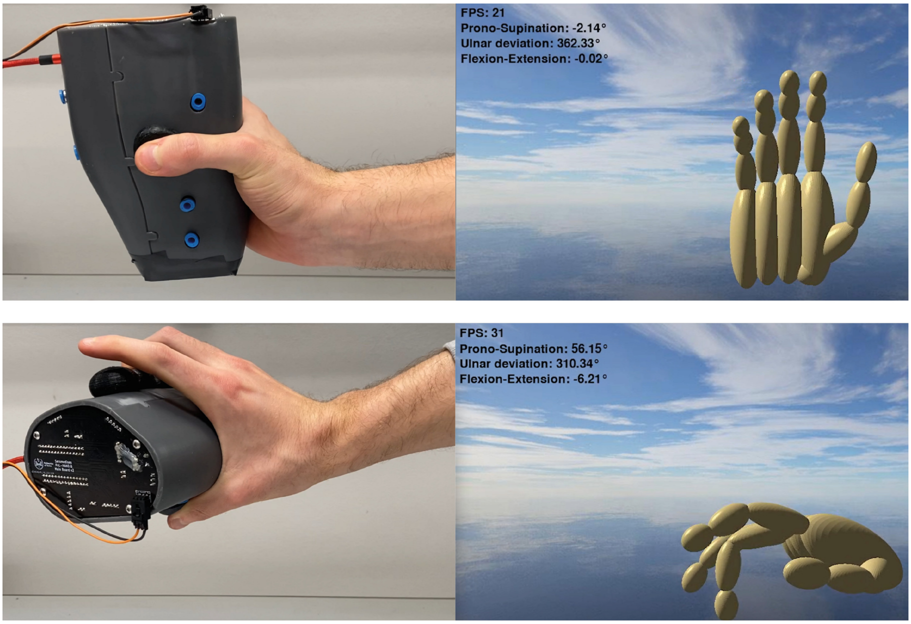


Fig. 7. Graphical representation of hand and finger motion in VR.

4 Discussion and Future Perspectives

What has been described above represents only the initial step toward the development of a fully functional device that patients requiring active finger rehabilitation can use. Among the key aspects not yet discussed but critical in this context is the study of grip ergonomics. This translates into the design of the rigid casing and the positioning of the membranes. Additionally, since PAL-HAND.Q is an integrated device, any decision regarding the geometry and dimensions of the casing directly impacts the placement of the components shown in Fig. 2. This, in turn, affects the distribution of mass, which loops back to influence the device's ergonomics during use.

Concerning the application contexts of PAL-HAND.Q, the development of immersive rehabilitation games typically revolves around the specific functionalities of the haptic device itself, i.e. the types of input and output signals it can handle. Such immersive games can relieve physiotherapists from repetitive tasks typically required during the active rehabilitation phase. This enables patients to take the device home and carry out rehabilitation exercises by simply connecting the device to a standard laptop or a generic screen.

Another noteworthy area of interest is the use of the haptic device to track recovery progress. Currently, this procedure is performed manually in medical centers, often involving a test designed to objectively evaluate the effectiveness of post-stroke rehabilitation. However, this process lacks standardization. A recent study conducted by Marek et al. [4] identified over 25 different methods used in the medical field for this purpose, classified according to the type of stroke (neurological, orthopedic, musculoskeletal). These methods aim to assess various parameters such as muscle strength, range of motion, movement execution, grasping ability, coordination, dexterity, responsiveness, and more.

Among the tests identified is the Purdue Pegboard Test, a time-based method where the goal is to place as many pegs as possible into holes on a specialized board within a 30-s time frame. The application described in Subsect. 3.2 is inspired by this test. Another example is the Frenchay Arm Test, which involves grasping and manipulating everyday objects, such as a comb, a cylindrical object, a ruler, and so on. Numerous variations of these tests exist, such as the Sollerman Hand Function Test or the Stroke Impact Scale Hand. These tests are based on having patients replicate movements from daily life to evaluate their kinematic capabilities (e.g., range of motion, speed), kinetic capabilities (e.g., muscle strength), or both.

In this regard, PAL-HAND.Q could serve as a tool for the objective quantification of stroke recovery by collecting raw data, which could then be classified according to the physiotherapist's requirements. For instance, using the peg-in-hole application as an example, the physiotherapist could remotely access information such as the number of objects correctly positioned during a routine, the patient's responsiveness, the duration of PAL-HAND.Q usage throughout the day, the level of stiffness applied, and more.

5 Conclusions

This paper described the early development of a handheld untethered device for finger active tele-rehabilitation contexts. The device is based on pneumatic technology, and consists of a five deformable bladders with adjustable stiffness that are positioned on a rigid case, that are used to provide selective multimodal haptic feedback on each user's finger. The functional design of the device and its early prototype had been described, and the possible contexts of use were shown using application software aimed at involving the user during rehabilitation routines. Further developments concern the use of the device not only as a tool for carrying out rehabilitation practices, but also as a tool for objective quantification of the patient recovery status. To this end, further research of PAL-HAND.Q requires collaboration with medical personnel to investigate whether PAL-HAND.Q is effective in assisting with the rehabilitation of finger stroke, and how the prototype should be further developed to be implemented in real clinical scenarios.

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