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Toward the Development of a Portable Handheld Device for Finger Interaction: Experimental Testing of PAL-HAND.Q

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Abstract
This paper presents a handheld portable device for haptic finger interaction based on Soft Pneumatic Sensing Chambers (SPSCs). After outlining the results of the hardware development, the study evaluates its effectiveness in collecting and analyzing user interaction data through exergames. The processed data showcase the potential of the device for intuitive and data-rich haptic interaction.

Keywords: Handheld device, Soft Robotics, Haptics, Variable Stiffness

1. Introduction

Wearable and handheld haptic interfaces for finger interaction have attracted significant attention in recent years due to their potential applications in virtual reality, teleoperation, and rehabilitation. These systems aim to provide tactile and kinesthetic feedback while maintaining portability and ease of use. Several portable devices have been proposed for hand assessment and training, such as GripAble [1] and Squegg [2], which enable hand strength evaluation and rehabilitation exercises. Wearable glove-based systems have also been investigated for VR-based hand rehabilitation and interaction [3].

In the context of virtual haptic interaction, different approaches have been explored to deliver tactile and force feedback at the finger level. Benko *et al.* [4] presented a handheld device capable of rendering virtual shapes while providing finger kinesthetic feedback. Choi *et al.* [5] introduced the CLAW device, a handheld exoskeletal interface providing force and vibrotactile feedback for single-finger interaction. Pneumatic and wearable solutions have also been investigated, such as the HaptGlove system proposed by Qi *et al.* [6] and the PIVOT wearable device for wrist force feedback introduced by Kovacs *et al.* [7].

Despite these developments, the design of compact haptic interfaces for finger interaction still presents several challenges. In wearable exoskeletal systems, misalignment between mechanical and human joints can generate parasitic forces that negatively affect user comfort [8]. Handheld solutions can mitigate these issues but often require a trade-off between device compactness and the richness of the haptic feedback they can provide [1], [2], [4].

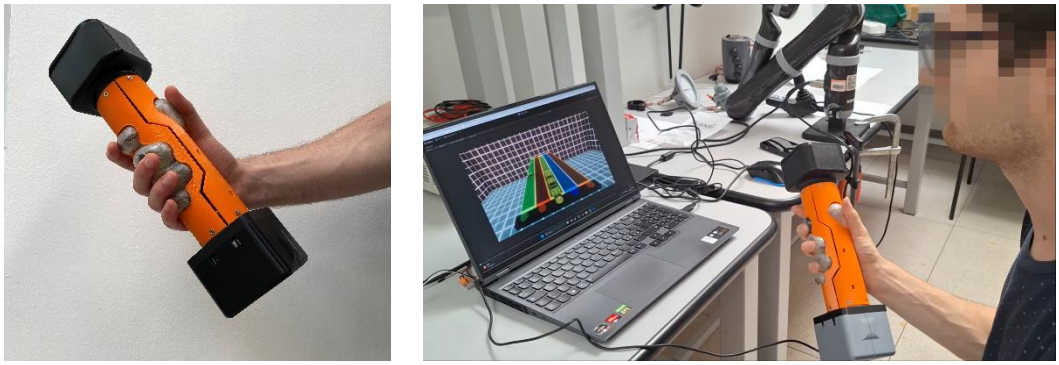
Inspired by these engineering challenges, the authors presented the concept and early prototyping of PAL-HAND.Q, an acronym for *Pneumatic and Lightweight Handheld Device* [9], [10]. The PAL-HAND.Q prototype is shown in Figure 1, and it is a solution designed to provide resistive force feedback through variable-stiffness pneumatic membranes. The system was



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conceived to preserve the portability advantages of handheld haptic interfaces while enriching the interaction capabilities through variable-stiffness finger interaction and the integration of multimodal feedback, including vibrotactile and auditory cues. Furthermore, the device design leverages soft robotics principles to promote safe and compliant interaction during finger-based tasks.

In this paper, we further develop the PAL-HAND.Q concept by presenting the latest hardware implementation of the device and reporting preliminary experimental results obtained from healthy subjects interacting with the device. The acquired data are discussed to demonstrate the device validity in finger exercise or active rehabilitation context.



(a) **(b)**

Figure 1 (a) The PAL-HAND.Q prototype, **(b)** a user playing exergames by using PAL-HAND.Q.

2. Handheld haptic device development

Figure 2 depicts the functional schematic of PAL-HAND.Q. Fingertip interaction is implemented via soft pneumatic sensing chambers (SPSCs) [11] to provide compliance and prevent from parasitic forces, mounted on a handheld "grab-and-go" structure. The core functionalities of PAL-HAND.Q include kinesthetic resistive finger feedback, independently controlled for each finger, with two adjustable stiffness levels ("soft" for dexterity-focused interaction and "hard" for higher force exercises). In this terms, the off-state bladder pressure is imposed with an external air supply through a check valve, while the volume of an auxiliary reservoir imposes the pressure-versus-squeezing level when the m-th valve is open. In addition, vibration is delivered to the finger pulp by means of eccentric rotating mass (ERM) motors, while a loudspeaker can provide indications to the user through audio inputs.

In terms of acquired data, the m-th finger motion is sensed indirectly through SPSC pressure level, while wrist rotation is tracked via an onboard inertial sensor.

The device sends and receives data to a remote-control unit (RCU) through wireless communication and power supply is provided by an on-board Li-Po battery, thus making PAL-HAND.Q completely untethered while in use. The last-developed PAL-HAND.Q prototype has a overall mass of approximately 500 g, a supply voltage of 3.7 V, peak power of 5 W and estimated autonomy of 1 hour.

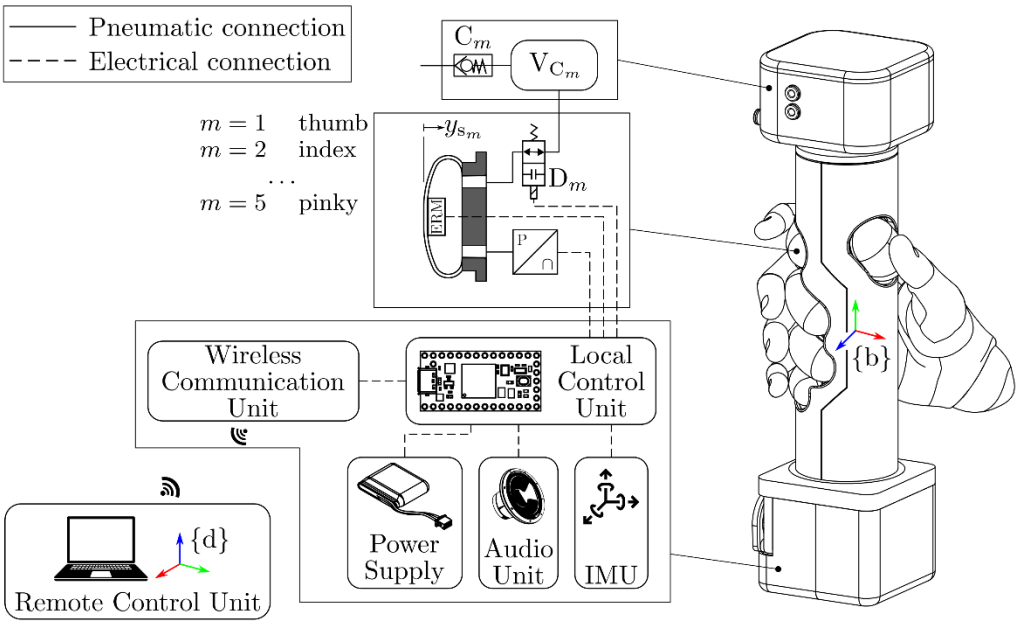


Figure 2 PAL-HAND.Q functional architecture.

2.1 Squeezing force estimation

A main advantage of the PAL-HAND.Q solution for finger-delivered haptic interaction is that the device can be used to estimate the force exerted by the user by making use of the pressure squeezing level. While this estimation presents considerable complexity, we propose a simplified approach derived from users' anthropometric hand data, following Buchholz methodology. To this aim, let F_{m} be squeezing force exerted by the user on the m-th soft bladder, and let A_{m} be the contact area between finger pulp and the bladder. Buchholz theory allows approximating phalanges as ellipsoidal geometries based on hand length HL and hand breadth HB [12], [13]. Literature studies demonstrate that the contact area is indeed elliptical in nature and dependent on factors such as applied normal force, nail presence, and physiological factors. For simplicity, we assumed the contact area constant and equal to a portion of the area derived from the Buchholz's model:

$$A_m = c\, A_{m,\mathrm{geometric}} = c\; 0.55\, \pi\, B_{m,4}\, HL\, H_{m,4}\, HB \tag{1}$$

where the coefficients $B_{\mathrm{m},4}$ and $H_{\mathrm{m},4}$ are listed in Table 1. The assumption that A_m is independent of contact depth y_s is supported by the system's operational characteristics, i.e. the pneumatic bladders are preloaded with an initial pressure, requiring exceeding a minimum force threshold to squeeze them. During this initial phase, the fingertip deforms until reaching a contact area that stabilizes within the operational range. Literature studies confirm that the contact area undergoes relatively moderate increases once the normal force threshold is exceeded [14], [15]. Regarding the coefficient c, we assumed a value of 0.8 for all five digits.

Table 1 Coefficients for estimating the elliptic semi-axes for the distal phalanges of the hand, extracted from [12]. Suffix $m$describes the digit number as in Figure 1. Last fixed suffix represents the distal phalanx as in [13].

m	1	2	3	4	5
$\mathbf{B}_{m,4}$	0.158	0.097	0.108	0.107	0.093
$\boldsymbol{H}_{m,4}$	0.113	0.093	0.094	0.091	0.084

3. Experimental tests

As described and developed, PAL-HAND.Q is designed to facilitate haptic interaction in general gaming contexts or in specific finger exercising applications, such as active finger rehabilitation. To this end, the ultimate goal is to create a complete pipeline in which multimodal haptic interaction (force, vibrotactile, audio), combined with modern gamification concepts, promotes the use of technology (Figure 3).

Therefore, we conducted a preliminary experiment of the technology using PC exergames as a test environment [16]. The integration between the custom device developed and the exergames is made possible by specially developed firmware, which allows data and command exchange between the on-board microcontroller and the laptop. The exergames are designed to exploit the data acquired by PAL-HAND.Q and the haptic feedback that can be generated. Hand movement is converted into the movement of a game character, e.g. by mapping pronation-supination movement to the track occupied by a vehicle or using the fingers to generate specific commands, while vibrotactile feedback is integrated into game events, e.g. incorrect command or completion of an activity.

Peculiar attention should be paid to force feedback. The two levels of stiffness are used in the game as follows. In the case of low stiffness (membranes perceived as soft and easy to press), the game focuses on coordination and response times, with a high number of commands required to complete the game and a relatively low level of effort perceived by the player. In the case of high stiffness (membranes perceived as hard and difficult to press), exergames focus on actual physical exercise, with few game events but high physical effort required to complete the actions on screen.

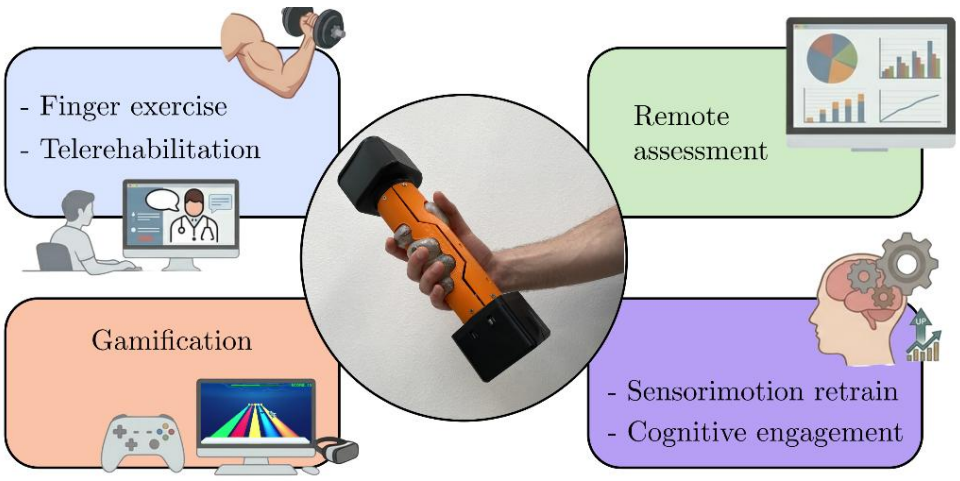


Figure 3 Features enabled by PAL-HAND and the intended context of use

3.1 Game experience and extracted data

Figure 4 shows experimental game data collected during a game session. This specific exergame uses the wrist motion to control a plane over five navigation lanes, while SPSCs are pressed to hit the spawning enemies. The blue line depicts how the user drove the plane over the gaming session, while the squared areas describe the characters spawning events, i.e. the game command requests events. Green-coloured boxes are for correctly hit characters, while a miss or plane collision are respectively depicted with dotted and red-coloured areas.

It can be observed that the user made several errors with the ring finger, firing shots even when there was no game input. This may be due to different gameplay factors, e.g., at t = 260 s there is first a delay in positioning and shooting, followed by a lack of coordination, while at t = 240 s this is caused by the joint squeezing of the ring and pinky digits, as described in Fig. 4 (b). In addition to the visual feedback, the airplane hit event as in Fig. 4 (c) generated a vibration on the finger of medium intensity lasting 200 ms, whereas the plane hit in Fig. 4 (d) generated three intermittent vibrations of higher magnitude, totally lasting 600 ms, on all five finger pulps.

Table 2 summarizes the gameplay data for both stiffness levels for the same user. For the high-stiffness mode, the SPSC squeeze thresholds are higher for the thumb and middle finger, followed by the index finger. Metrics such as the number of pronation–supination or ulnar–radial deviation movements, the number of SPSC squeezes per finger, and the average hold time for each membrane could serve as relevant parameters to map the user interaction rate and mobility level. In medical tele-rehabilitation applications, these metrics could be used to adapt the game based on the minimum number of movements required per finger during a single training session, or minimum level of squeezing force required.

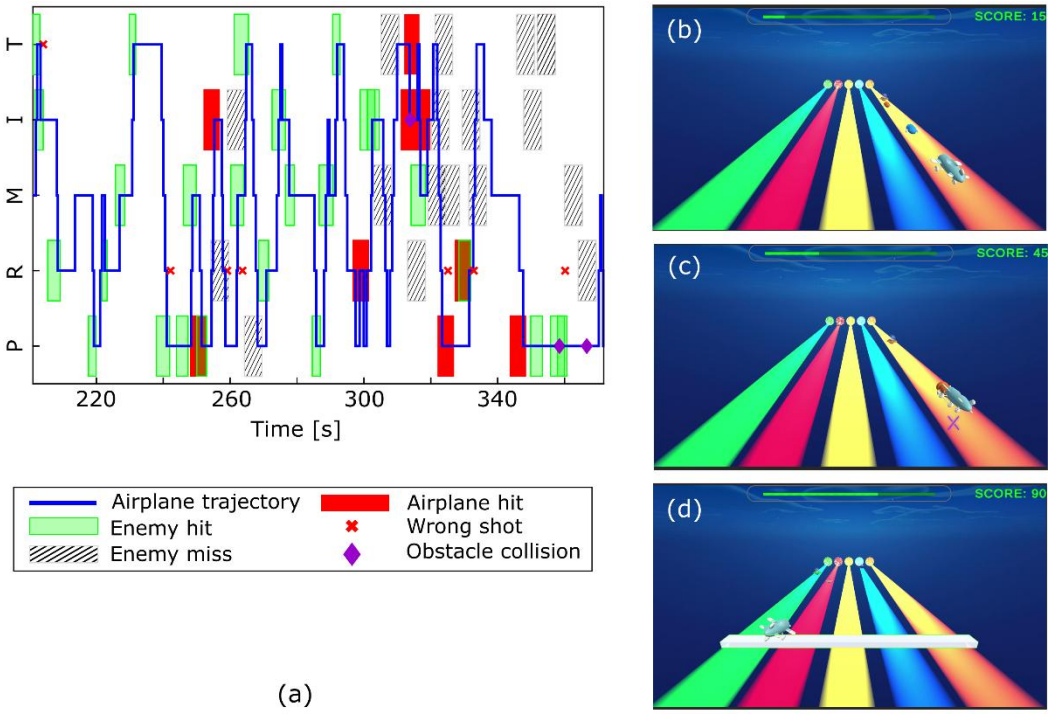


Figure 4 Game experience during the airplane exergame in low-stiffness mode: **(a)** overall gameplay plot; **(b)** joint squeezing of the ring and pinky SPSCs at t = 240 s; **(c)** airplane hit at t = 250 s; (d) obstacle hit at t = 320 s.

Table 2 Elaborated data measured by PAL-HAND.Q in both stiffness bodes during the demo session. SPSC numbering is as defined in Figure 2 (1=thumb, 2=index, ..., 5=little). $F_{\text{thresh.}}$ is the force threshold value to detect the m-th SPSC squeezing for the generation of game events. Third row represents the number of detected SPSC squeezing, and t_{hold} is the average pressing time. Last section of the table reports the wrist motion data, i.e. number of detected pronation-supination and radial-ulnar deviation detected, as well as their average angular rate.

	Low-level stiffness mode					**High-level stiffness mode**				
$\boldsymbol{m}$	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
$\boldsymbol{F_{\text{thresh.}}}$ **[N]**	6.6	3.7	4.1	4.0	3.4	23.6	7.3	9.2	6.1	5.0
SPSC press no.	5	4	6	10	8	4	4	7	8	9
$\boldsymbol{t_{\text{hold}}}$	0.44	0.5	0.38	0.63	0.39	0.42	0.39	0.44	0.51	0.49
Command success rate	44	36	54	44	58	44	36	54	44	83
Pron./Sup. Motion no.	43/45					59/60				
Angular rate [deg/s]	+186/-224					+181/-189				
Ulnar/Radial dev. No.	21/21					17/17				
Angular rate [deg/s]	+183/-178					+191/-129				

4. Conclusions

This paper presented the development of a handheld haptic device designed to provide multimodal finger experience. The device exploits the advantages of soft robotics to ensure safe and compliant interaction, while its design enables independent multimodal haptic feedback in a portable and untethered solution. Experimental results demonstrate its ability to provide information-rich interaction while collecting valuable data from user inputs. Future work will investigate how the device design affects perceived comfort, usability, and overall user experience.

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