User Experience of PAL-HAND.Q, a Pneumatic Haptic Device for Finger-Level Gaming Interaction

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Abstract: This study investigates the usability and user experience of PAL-HAND.Q, a handheld haptic device designed to provide independent haptic feedback on each finger through an integrated electro-pneumatic system. The device features five soft pneumatic membranes—one per finger—enabling vibrotactile stimulation and variable stiffness feedback. We conducted a usability study using two games that leverage the device's key features: Tile Game, which emphasizes timed actions and finger coordination, and Airplane Game, which integrates finger pressing with device orientation control. Twenty-five participants tested the system and completed questionnaires on usability, workload, game experience, haptic experience, and comfort. The results indicate good usability, moderate perceived workload, and engaging interactions. Notably, the device demonstrated better performance in continuous control tasks compared to time-pressured precision tasks, suggesting its suitability for applications requiring sustained, smooth finger-level interaction. Overall, the findings demonstrate PAL-HAND.Q's effectiveness for finger-level gaming interaction and point to its potential applicability in other domains requiring portable, independent finger-level haptic control, such as virtual and augmented reality, rehabilitation, and interactive training systems.

1 INTRODUCTION

In their initial conception, haptic systems were designed as robotic platforms enabling human–machine interaction (HMI) through the sense of touch. Over time, this terminology has expanded to include any type of stimulus involving the user's senses — such as force, vibration, visual or auditory feedback (Culbertson et al., 2018) — thereby broadening its applications beyond robotics into entertainment (Saint-Louis and Hamam, 2021), social interfaces (Jacucci et al., 2024), and rehabilitation (Ozioko and Dahiya, 2022; Irigoyen et al., 2024). During the last decades, the use of haptic devices for interactive gaming has gained particular attention, offering users more engaging and immersive experiences through realistic and multimodal feedback (Heredia et al., 2019; Makin et al., 2019).

Recent advances in wearable and handheld haptic systems have opened new opportunities for accessible and portable interaction in virtual and augmented environments. Unlike grounded or exoskeletal systems, handheld controllers combine mobility and immediacy of use, making them particularly suitable for gaming contexts where comfort and responsiveness are critical. However, a persistent technical challenge lies in achieving a trade-off between device compactness and the richness of haptic feedback (Ozioko and Dahiya, 2022). Compact controllers often sacrifice realism or force fidelity, whereas systems offering rich kinesthetic feedback tend to become bulky or tethered (Benko et al., 2016; Choi et al., 2018; Qi et al., 2023).

In this context, our work focuses on the user experience (UX) of PAL-HAND.Q (Duretto et al., 2024; Colucci et al., 2025), an acronym for *Pneumatic and Lightweight Handheld Device*, a lightweight, fully untethered handheld haptic controller that delivers

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finger-level feedback for interactive experiences. In this work (Fig. 1), we contribute in two main areas: first, we explore PAL-HAND.Q as a controller with 25 participants to assess perceived workload, usability, and engagement using state-of-the-art questionnaires and corresponding analyses; and second, an objective and subjective evaluation of handheld grip comfort.

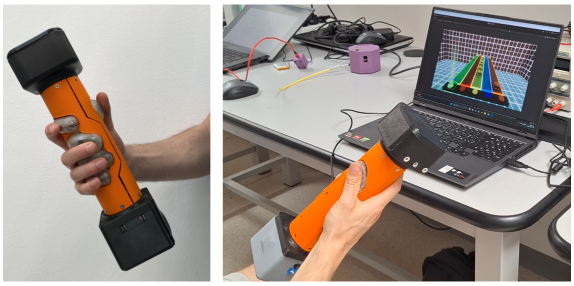


Figure 1: PAL-HAND.Q device (left) and usability study setup (right).

2 RELATED WORK

Across research domains on haptic interfaces (Culbertson et al., 2018; Saint-Louis and Hamam, 2021; Jacucci et al., 2024), the common goal is to enhance user engagement and realism through multimodal feedback combining tactile, kinesthetic, and sometimes auditory or visual stimuli (Heredia et al., 2019; Makin et al., 2019). In the context of human–computer interaction (HCI), a growing body of work focuses on portable haptic systems that support natural hand interaction in virtual or gaming scenarios. These systems can broadly be categorized by their form factor (wearable or handheld) and the type of feedback provided (tactile, kinesthetic, or hybrid).

Hand Wearable Devices. Hand wearable haptic devices are mechanical systems worn on the hand and fingers to sense motion and deliver feedback. They are commonly classified according to the functionalities they provide: hand and finger pose tracking (Tr.), kinesthetic feedback (KF), and tactile feedback (TF).

Several devices focus on hand and finger pose estimation (Caeiro-Rodríguez et al., 2021; Ozioko and Dahiya, 2022). Examples include the untethered RAPAEL Smart Glove, which uses a 9-axis IMU and resistive sensors to estimate 8 DOFs (Shin et al., 2016), and the Metagloves Pro, capable of tracking up to 25 DOFs MANUS (2025).

Kinesthetic feedback can be either passive, where the device provides resistive forces, or active, where forces are actively applied to the user. Dexmo (Gu et al., 2016) exemplifies an active rigid exoskeleton providing both hand tracking and independent finger KF, while SenseGlove Nova 2 SenseGlove (2023) adopts a cable-driven passive approach and integrates limited TF via vibrotactile actuators.

Handheld Devices. Handheld devices adopt a grab-and-go design philosophy, prioritizing portability and immediate interaction. Strict mass and size constraints, compared to wearable systems, typically limit the range and fidelity of feedback they can provide. Mechanically actuated handheld devices have been proposed to deliver rich kinesthetic feedback. NormalTouch Benko et al. (2016), for example, enables 3D shape rendering in VR using a 4×4 pin matrix, while active finger KF is provided via a compact parallel mechanism (Wang et al., 2021). Similarly, the CLAW device Choi et al. (2018) offers single-finger active KF and TF through a rigid exoskeletal structure, supporting interaction tasks such as grasping and pressing.

Overall, handheld designs expose a trade-off between feedback richness and compactness. While rigid mechanical systems achieve high-fidelity force feedback, their weight and form factor can reduce comfort. Softer solutions, such as pneumatic or cable-driven approaches (e.g., HaptGlove Qi et al. (2023)), improve compliance but often depend on external components that limit mobility.

Positioning of PAL-HAND.Q. Wearable haptic devices offer rich functionality but require gloves or finger-mounted components, often reducing portability, ease of use, and perceived comfort (Dittli et al., 2021). Conversely, handheld devices face stricter mass and encumbrance constraints, which typically limit the number of involved fingers, feedback modalities, or result in tethered configurations.

Within this context, PAL-HAND.Q (Duretto et al., 2024; Colucci et al., 2025) positions itself as an untethered handheld device that balances portability and functionality. It provides hand and finger motion tracking together with both kinesthetic and tactile feedback on all five fingers, while preserving a grab-and-go form factor. Fingertip interaction is enabled through soft pneumatic sensing chambers (SPSCs) (Tawk et al., 2019) integrated into a compliant handheld structure.

PAL-HAND.Q delivers independently controlled resistive kinesthetic feedback on each finger, with two selectable stiffness levels tailored to either dexterous interaction or higher-force exercises, and localized vibrotactile feedback at the fingertips. Finger motion and applied forces are inferred from SPSC internal pressure, while wrist rotation is tracked via an onboard inertial sensor. Compared to existing wearable and handheld solutions, PAL-HAND.Q intentionally sacrifices higher finger DOFs and complex active mechanisms in favor of improved portability, comfort, and safety, avoiding rigid joint coupling and the associated parasitic forces (Tawk et al., 2019).

3 METHODS

This study represents an evaluation of the PAL-HAND.Q system, conducted to assess its functionality, user experience, and ergonomic suitability as an interaction device in controlled, game-like scenarios. To this end, we adopted a gamified approach that leverages motivational elements of game design to promote engagement.

Based on established literature on motor training and dexterity assessment (Olafsdottir et al., 2008), we developed two games aimed at testing users' finger coordination, strength, and wrist control, and the effectiveness of a 5-finger interface. These games can be played on a desktop computer and were created to test different aspects of PAL-HAND.Q's multimodal interaction, focusing on precision and continuous control tasks.

3.1 Experimental Protocol

Upon arrival, participants were seated at the workstation, where demographic data and hand measurements were collected, followed by a brief introduction to the experiment. The facilitator then positioned PAL-HAND.Q in the participant's hand and conducted a short tutorial, including calibration of the membrane interaction thresholds according to individual finger strength.

Participants subsequently completed two gaming sessions, each involving a different game (*Tile Game* and *Airplane Game*, Fig. 2), played under two membrane configurations: soft (low resistance, *dexterity* mode) and hard (high resistance, *force* mode). The order of the games was counterbalanced across participants.

After the first session, participants completed the System Usability Scale (SUS) (Brooke et al., 1996), raw NASA Task Load Index (NASA-TLX) (Hart and Staveland, 1988; Byers, 1989; Said et al., 2020), In-game Game Experience Questionnaire (GEQ) (IJsselsteijn et al., 2013), and the Haptic Experience Inventory (HXI) (Shi and Schneider, 2025). The same questionnaires were administered again after the second session, with the addition of the Comfort Questionnaire for Hand Tools (CQH) (Kuijt-Evers et al., 2004). Each game lasted approximately 4.5 minutes and was played twice, resulting in a total session duration of about 38 minutes per participant.

3.2 Device Tutorial: Using PAL-HAND.Q

Since users are unlikely to be familiar with PAL-HAND.Q, the experience starts with a short tutorial introducing its haptic and motion-sensing capabilities. A digital twin mirrors the device's rotations and membrane compression, guiding users through the basic interactions. The tutorial first asks users to press each membrane in response to vibration cues, showcasing independent membrane actuation and introducing the two operating modes (*dexterity* and *force*). During this step, the system calibrates the force-mode interaction to each user's finger strength. Pressing force F_{m} is inferred from gauge pressure by estimating contact area using anthropometric hand-size data and literature coefficients (Buchholz et al., 1992; Buchholz and Armstrong, 1991). Two force thresholds are then defined for each membrane to avoid accidental activation or release. Finally, users perform simple wrist movements, including radial–ulnar deviation and pronation–supination.

3.3 Games

Each game contains a short in-game introduction and require active interaction from all the fingers contrary to standard VR controller that mostly rely on thumb-index-middle interactions. The force required from the user varies by game mode, enabling a further level of interaction and a deeper experience analysis.

By combining visual, auditory, and haptic cues, the applications engage multiple sensory channels to inform users of their successes and mistakes.

Tile Game serves as a testbed for evaluating the device's ability to support precise finger timing and coordination. The user engages in a music-based challenge in which each note of a selected channel of a MIDI track is linked to a virtual tile whose length reflects the duration of the note. Each tile is assigned to a different lane, each corresponding to one of the five physical membranes, thus encouraging precise use of the fingers. When the tiles appear and move towards a target line, the user must press the associated membrane at the exact moment the note is heard and for the duration of the note, keeping up with the tempo of the song. Alongside visual cues, the game provides finger-specific haptic feedback: a continuous sawtooth vibration accompanies long notes while they are being pressed, and a brief vibration signals

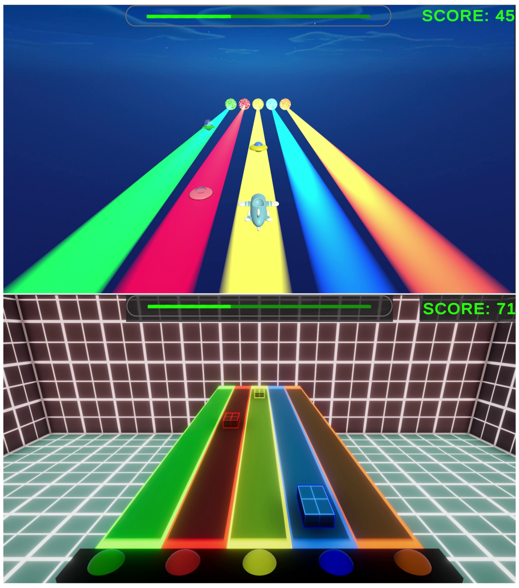


Figure 2: Snapshots of the two games implemented in the study: Airplane Game (top) and Tile Game (bottom).

missed notes, ensuring clear and independent feedback for each membrane.

Airplane Game is designed to assess complex multimodal coordination by combining membrane pressing with wrist-based motion control. The user enters a scenario in which he has to shoot at incoming enemies while piloting an airplane. The mechanics are the same as Tile Game: each enemy appears in a lane associated with a specific membrane and finger. To succeed, players must not only press the correct membrane but also align the airplane with the corresponding lane and avoid obstacles along the way. PAL-HAND.Q's onboard inertial measurement unit (IMU) allows players to maneuver the aircraft through wrist movements such as pronation–supination and abduction–adduction, providing an additional interaction mode. Vibrations are used to provide feedback: three intermittent pulses accompanied by airplane blinking indicate a collision with an obstacle, while a single short vibration on the finger corresponding to the lane indicates contact with an enemy.

3.4 Data Analysis

We employed a combination of descriptive, inferential, and predictive statistical methods to analyze the data collected through questionnaires across the game sessions, each consisting of one of the two games (Tile or Airplane Game), played sequentially under both membrane configurations (dexterity and force mode). To examine differences between conditions, we employed the Mann–Whitney U test and the Wilcoxon signed-rank test, calculating the effect size (r) for each comparison. To explore associations between measures, we conducted Pearson's correlation analyses and, finally, we performed linear regression analyses using the Ordinary Least Squares (OLS) method, in order to test predictive relationships between the measures. All analyses were carried out with a significance threshold of $\alpha = 0.05$.

4 RESULTS

The study involved 25 participants aged 20 to 51 years, with the majority (16 participants) between 25 and 32 years old. Of the participants, 68% were men (n = 17) and 32% were women (n = 8). 4 participants were left-handed.

This initial testing phase aimed to identify early usability issues, such as discomfort, while also collecting qualitative feedback to inform future device iterations. None of the participants reported pre-existing hand mobility issues. In the following sections, we analyzed the collected data dividing them by game session and game type when needed, and report descriptive statistics using M to indicate the mean and SD for the standard deviation.

4.1 Usability and Workload

Usability and perceived workload were measured respectively with the SUS and NASA-TLX, both administered after each game was played in both membrane modalities.

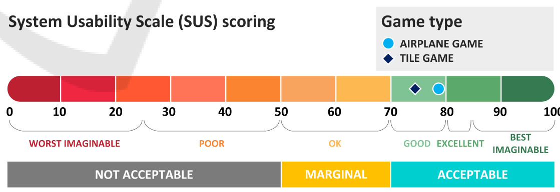


Figure 3: Average SUS results for each game across sessions.

Game-type analyses (Fig. 4) showed that Airplane Game achieved slightly higher usability and marginally lower workload than Tile Game (SUS: $M = 78.7$ vs 73.5, $r = 0.22$, $p = 0.331$; TLX: $M = 44.6$ vs 45.6, $r = 0.83$, $p = 0.47$), although differences were not statistically significant. Overall, both games fell within a "good" usability range and induced moderate workload (Fig. 3).

Session-based analyses revealed stable SUS scores across sessions, but a significant increase in TLX from the first to the second session ($M = 41.33$

to 48.91, $r = 0.68$, $p < 0.05$), suggesting cumulative muscular or cognitive fatigue associated with repeated finger and wrist actuation (Fig. 4).

Game type and session-based analyses indicated an interaction between game type and play order. While usability ratings were comparable when games were played first, Tile Game was rated lower when played second (Fig. 5), with a difference of approximately 10 SUS points ($r = 0.35$, $p = 0.081$) compared to Airplane Game (Fig. 5). This effect suggests an order-dependent perception rather than a simple learning effect, potentially due to the higher precision and timing demands of Tile Game.

System level analyses were performed by averaging SUS and TLX values across all games and sessions for each participant, to provide a measure of the system's overall usability. This choice was motivated by the high similarity of results across conditions and by the absence of statistically significant differences. Correlation analyses based on these aggregated scores show a significant negative relationship between SUS and TLX ($r = -0.45$, $p = 0.001$), indicating that higher usability of the device is associated with reduced workload. Regression models confirmed this: TLX was significantly predicted by SUS ($R^2 = 0.22$, $p = 0.003$).

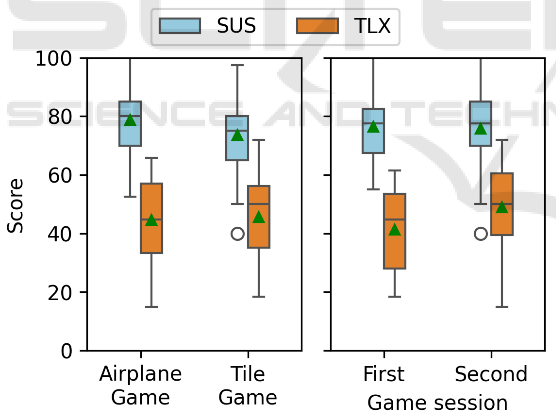


Figure 4: Comparison of SUS and TLX scores by game type (left) and by game session (right).

4.2 Game Experience and Engagement

Player experience was assessed using a slightly modified GEQ, removing items related to sensory and imaginative immersion that were not relevant for our context.

Game-type analyses (Fig. 6) indicated that Airplane Game was generally perceived as slightly more engaging than Tile Game. Higher mean scores were observed for competence, flow, challenge, and pos-

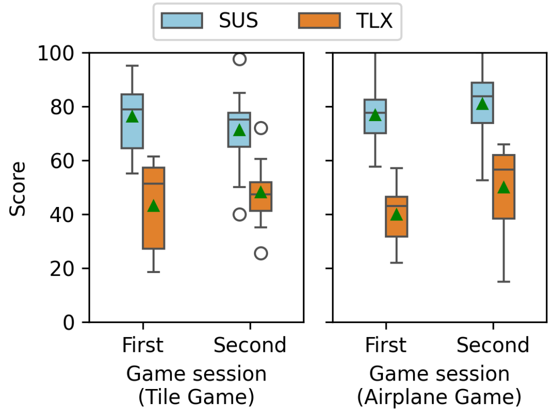


Figure 5: Comparison of SUS and TLX scores by session order for the Tile Game (left) and the Airplane Game (right).

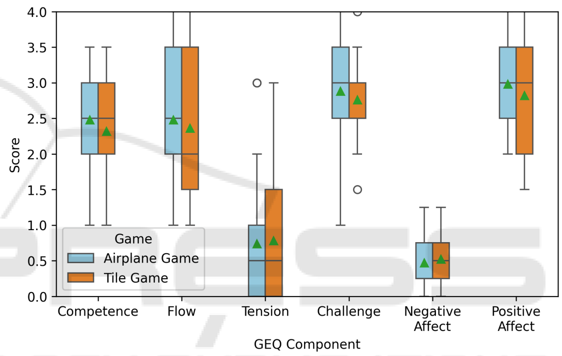


Figure 6: Distribution of GEQ category scores across the two games: *Airplane Game* and *Tile Game*.

itive affect, while tension and negative affect were marginally lower. Although none of these differences reached statistical significance, the pattern suggests that continuous control tasks better support engagement and perceived competence.

Session-based analyses (Fig. 7) revealed only minor changes across sessions. Competence, flow, and positive affect showed slight increases in the second session, accompanied by small increases in tension and negative affect and a slight reduction in challenge. These trends, although non-significant, are consistent with a limited effect of accumulated fatigue.

Game type and session-based analyses (Fig. 8) highlighted an order effect. When played second, Airplane Game showed higher flow and competence while maintaining high positive affect, suggesting that familiarization with the device supports sustained engagement in continuous interaction tasks. In contrast, Tile Game exhibited reduced flow and increased tension and negative affect when played second, consistent with the higher precision and timing demands of

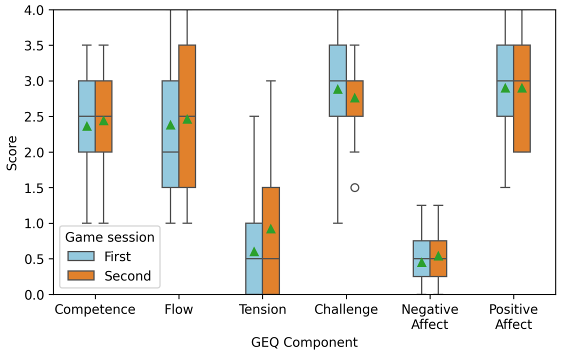


Figure 7: Distribution of GEQ category scores by game session (*first* vs. *second*).

the task.

System-level analyses were also performed, averaging GEQ across games and sessions. Higher usability (SUS) was positively correlated with competence ($r = 0.31$, $p = 0.026$) and positive affect ($r = 0.39$, $p = 0.005$), and negatively with tension ($r = -0.41$, $p = 0.003$) and negative affect ($r = -0.48$, $p < 0.05$). Conversely, higher workload (TLX) was associated with increased tension ($r = 0.48$, $p < 0.05$) and negative affect ($r = 0.41$, $p = 0.003$) and reduced positive affect ($r = -0.38$, $p = 0.007$). Regression analyses confirmed these relationships, indicating that usability predicts improved engagement and affect, whereas workload predicts heightened tension and negative emotional responses.

4.3 Haptic Experience

HXI results were analyzed after each game session to evaluate the quality of haptic interaction. "Good" scores were defined as means above 4 on the 1–7 Likert scale and low Discord values, and correlations with SUS, TLX, and GEQ were examined.

Game-type analyses (Fig. 9) showed no significant differences between Tile and Airplane Games. All dimensions (Autotelics, Involvement, Realism, Harmony, Discord) were comparable across games, indicating that PAL-HAND.Q provides consistent haptic feedback under different control demands.

Session-based analyses (Fig. 10) revealed generally positive haptic experiences, with slight declines in Involvement and Harmony and marginally higher Discord in the second session ($M = 2.83$, $SD = 1.39$ vs. $M = 2.43$, $SD = 1.18$, $r = 0.33$, $p = 0.264$). These trends suggest a mild effect of adaptation or fatigue during prolonged device use.

Game type and session analyses (Fig. 11) highlighted an asymmetry: Tile Game scores declined when played second (Involvement: $M = 5.56 \rightarrow 4.73$, $r = 0.48$, $p = 0.017$), with smaller drops in Realism and Harmony and an increase in Discord. Airplane Game showed stable or slightly improved scores when played second, indicating more robust haptic perception for continuous, less precision-demanding tasks.

System-level analyses revealed that Harmony positively correlated with SUS ($r = 0.31$, $p = 0.029$) and negatively with TLX ($r = -0.37$, $p = 0.008$), while Discord showed the opposite pattern (SUS: $r = -0.43$, $p = 0.002$; TLX: $r = 0.43$, $p = 0.002$). GEQ correlations further confirmed these trends: Harmony linked to reduced tension ($r = -0.44$, $p = 0.002$), Discord to increased tension ($r = 0.42$, $p = 0.003$) and negative affect ($r = 0.49$, $p < 0.05$), and Involvement positively associated with positive affect ($r = 0.37$, $p = 0.009$). Overall, more harmonious and coherent haptic feedback supports positive user experience and engagement.

4.4 Handheld Grip Comfort Assessment

The assessment of grip comfort plays a key role in the design and refinement of the geometry of handheld devices (Bisht and Khan, 2013). To this end, we adapted the CQH questionnaire Kuijt-Evers et al. (2004), selecting the items we considered most relevant for our experimental setting.

Users rated ease of use, suitability for gaming, and perceived device quality positively ($r \approx 0.7$, $p < 0.05$; quality $r = 0.48$, $p = 0.03$), while discomfort-related items (numbness, lack of tactile sensitivity) received low scores ($r = -0.85$, $p < 0.05$). Required grip force showed a median below neutral (3; $r = -0.53$, $p = 0.015$), suggesting room for ergonomic improvement. Other descriptors (hand adaptation, ease of pressing SPSCs, and handle comfort) were rated near neutral.

As for the exerted pressure recorded during the gaming sessions, the forces generated in force mode were higher than in the dexterity one for both genders, reflecting the increased stiffness of the membrane. In dexterity mode, male and female participants achieved comparable force levels, while in force mode males exhibited higher p and consequently higher F across all fingers. The thumb produced the largest forces, followed by the middle finger and the index. The mean thumb-to-index force ratio in force mode was 2.5 for males and 2.6 for females, while the thumb-to-middle ratio was 2.0 and 2.2, respectively. It is also worth noting that the SD was larger in force mode for most fingers, with the exception of the little finger. This variability justifies the implementation of custom thresholds for game event generation, particularly under the hard SPSCs condition (force mode). Regarding wrist dexterity in prona-

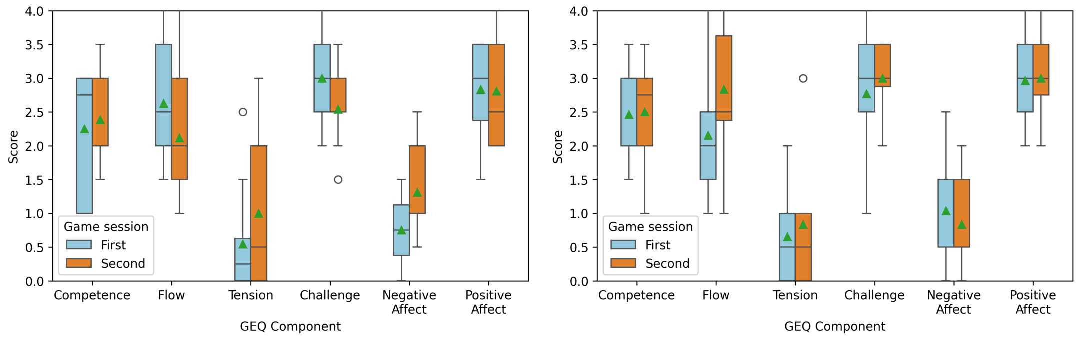


Figure 8: Comparison of GEQ category scores by game (Tile Game on the right, Airplane Game on the left) and session.

Table 1: Mean (SD) of maximum gauge pressures (p) and forces (F) under dexterity and force modes, and peak wrist angular velocities, by gender.

	Finger	$p_{\text{max,dexterity}}$ **[bar] gauge**	$F_{\text{max,dexterity}}$ **[N]**	$p_{\text{max,force}}$ **[bar] gauge**	$F_{\text{max,force}}$ **[N]**	**+ Pronation - Supination [deg/s]**	**+ Ulnar - Radial [deg/s]**
Male n=17	1	0.24 (0.02)	11.41 (1.51)	0.60 (0.18)	28.29 (9.49)	+ 228.71 (146.96) - 227.26 (123.72)	+ 201.83 (97.89) - 229.79 (123.69)
	2	0.22 (0.05)	5.18 (1.38)	0.48 (0.14)	11.54 (3.80)		
	3	0.21 (0.04)	5.69 (1.30)	0.54 (0.18)	14.50 (5.66)		
	4	0.19 (0.06)	4.88 (1.73)	0.41 (0.15)	10.66 (4.42)		
	5	0.19 (0.03)	3.81 (0.72)	0.45 (0.14)	9.34 (3.19)		
Female n=8	1	0.24 (0.01)	10.05 (0.25)	0.49 (0.16)	20.10 (6.11)	+ 200.09 (93.74) - 215.14 (91.32)	+ 226.12 (130.26) - 226.51 (104.89)
	2	0.20 (0.03)	4.08 (0.66)	0.38 (0.10)	7.82 (1.97)		
	3	0.19 (0.03)	4.53 (0.79)	0.40 (0.12)	9.33 (2.76)		
	4	0.18 (0.05)	3.96 (1.06)	0.33 (0.06)	7.40 (1.19)		
	5	0.17 (0.04)	3.04 (0.66)	0.37 (0.03)	6.61 (0.63)		

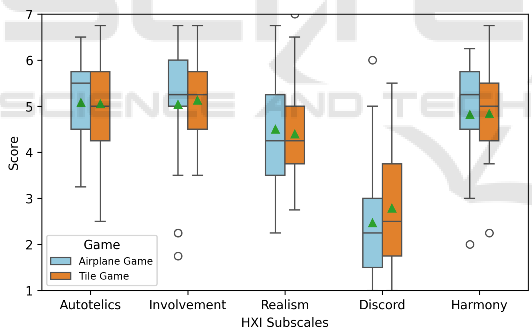


Figure 9: Distribution of HXI subscale scores across the two games: *Airplane Game* and *Tile Game*.

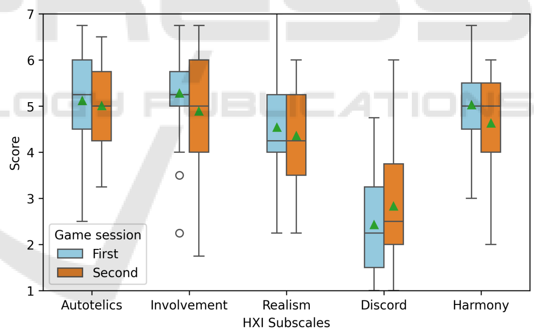


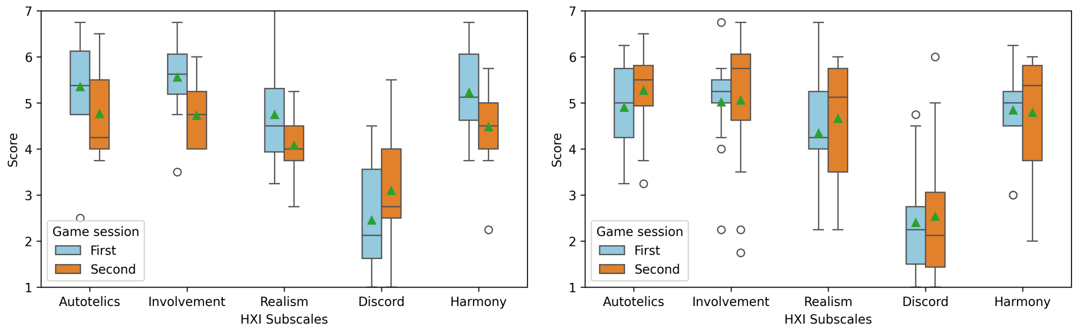
Figure 10: Distribution of HXI subscale scores by session order (*first* vs. *second*).

tion–supination and radial-ulnar deviation, no relevant differences were observed between male and female participants.

4.5 Discussion of Results

Usability and workload metrics were consistent with benchmarks for similar haptic devices (Ranzani et al., 2021; Guillén-Climent et al., 2021; Saric et al., 2022), confirming PAL-HAND.Q as a valid gaming controller. Continuous-control tasks (Airplane Game) yielded slightly higher usability and lower workload, while time-pressured precision tasks (Tile Game) increased effort and fatigue. Usability remained stable across sessions, but workload rose in the second session, reflecting adaptation or fatigue. Game order influenced perception: playing Airplane Game first reduced Tile Game usability, whereas playing Tile Game first enhanced Airplane Game experience, suggesting that ergonomics and interaction modes should account for precision-demanding tasks.

Game experience analyses indicated generally positive outcomes: moderate competence and flow, high challenge and positive affect, and low negative affect and tension. Engagement was robust during continuous-control tasks, but fragile under time-



(a) *Tile Game*: HXI subscale scores by session. (b) *Airplane Game*: HXI subscale scores by session.

Figure 11: Comparison of HXI subscale scores across games and gameplay sessions.

Table 2: CQH item descriptive statistics reported as Median (IQR); scale 1–7, neutral = 4; $n = 25$.

Descriptor of comfort/discomfort	Median (IQR)
Fits the hand	4 (2.25)
Is well suited for playing the games provided	5 (2.00)
Is easy to use	5 (2.00)
It is easy to apply force to the membranes with the fingers	4 (1.00)
Is a high quality tool	5 (2.00)
Has a nice feeling handle	4 (2.25)
Needs low hand grip force supply	3 (2.00)
Has a good friction between handle and hand (no slippage)	4 (3.00)
Causes an inflamed skin of hand	1 (0.00)
Causes peak pressure on the hand	2 (1.5)
Feels clammy	2 (2.25)
Causes numbness and lack of tactile feeling in the hand	2 (2.00)
Causes cramped muscles	3 (2.25)

critical precision, especially when Tile Game was played second. Correlations confirmed that usability promotes competence and enjoyment, while workload predicts frustration and tension, highlighting that minimizing effort is crucial for motivation and emotional engagement.

Haptic experience (HXI) showed coherent, harmonious feedback, with high involvement, realism, and autotelic scores and low discord. Tile Game suffered a decline in haptic quality when played second, whereas Airplane Game remained stable or improved, indicating that PAL-HAND.Q supports continuous interactions more naturally. Correlations with SUS, TLX, and GEQ confirmed that harmonious haptics enhance usability, reduce workload, and foster positive affect, emphasizing haptic consistency as central to interaction quality.

Grip comfort reinforced these findings: subjective and objective assessments confirmed overall comfort and suitability, while highlighting ergonomic refinements—particularly handle geometry and internal mass distribution—could reduce fatigue and preserve haptic quality, especially in demanding precision tasks. Adaptive thresholds for force-mode interactions further reduce effort, and CQH responses suggest that lowering required grip force would enhance prolonged interaction. Overall, grip ergonomics are key to sustaining usability, minimizing workload, and maintaining haptic engagement.

4.6 Limitations

The current prototype was originally designed based on a right male hand. While design analyses for a left-hand version have been conducted, the present study considered only the right-hand device, since the left-hand model is not yet available. In terms of hardware, the soft pneumatic sensing chambers (SPSCs) provide a maximum stroke of approximately 13 mm, which does not fully exploit the natural range of motion of the fingers. These design constraints may limit the applicability of the device for tasks requiring larger finger excursions. Ongoing work aims to improve the device's adaptability to a wider variety of hand sizes and morphologies, as well as to extend the effective range of finger movement.

5 CONCLUSION

In this paper, we assessed the User Experience of PAL-HAND.Q, in terms of usability, workload, gaming and haptic experience, and comfort through Tile Game and Airplane Game. The results showed good usability and engaging interactions overall, but also a higher workload and fatigue across gaming sessions. In future developments, we intend to refine the usability of our system through prototype advancements and new interaction dynamics. In particular, we aim to leverage the possibility of controlling SPSCs stiffness onto a continuous domain, enabling continuous resistive force feedback control. Future developments will also include the integration of further vibration stimuli, with systematic investigation into their optimal role, whether reinforcing visual feedback or prompting user actions. Along with these improvements, we plan to verify PAL-HAND.Q functionality as an interaction device in extended reality scenarios. Furthermore, we plan to extend the sample of testers by including more women, left-handed users, and a broader age range to strengthen the diversity and generalizability of our findings. The selected games reproduce motion patterns relevant to clinical rehabilitation (finger coordination, wrist rotation), and the device allows the pressure required on each membrane to be independently adjusted. Building on the successful tests with healthy participants, we plan to evaluate PAL-HAND.Q as a rehabilitation tool for clinical populations.

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