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PalmEx: Adding Palmar Force-Feedback for 3D Manipulation with Haptic Exoskeleton Gloves

Elodie Bouzbib, Marc Teyssier, Thomas Howard, Claudio Pacchierotti and Anatole Lécuyer

Abstract—Haptic exoskeleton gloves are a widespread solution for providing force-feedback in Virtual Reality (VR), especially for 3D object manipulations. However, they are still lacking an important feature regarding in-hand haptic sensations: the palmar contact. In this paper, we present PalmEx, a novel approach which incorporates palmar force-feedback into exoskeleton gloves to improve the overall grasping sensations and manual haptic interactions in VR. PalmEx's concept is demonstrated through a self-contained hardware system augmenting a hand exoskeleton with an encountered palmar contact interface – physically encountering the users' palm. We build upon current taxonomies to elicit PalmEx's capabilities for both the exploration and manipulation of virtual objects. We first conduct a technical evaluation optimising the delay between the virtual interactions and their physical counterparts. We then empirically evaluate PalmEx's proposed design space in a user study (n=12) to assess the potential of a palmar contact for augmenting an exoskeleton. Results show that PalmEx offers the best rendering capabilities to perform believable grasps in VR. PalmEx highlights the importance of the palmar stimulation, and provides a low-cost solution to augment existing high-end consumer hand exoskeletons.

Index Terms—Haptics, Virtual Reality, Artefact, Exoskeleton, ETHD, Encountered-type of Haptic Device, On-demand

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1 INTRODUCTION

THE promise of future interactive virtual environments has raised various questions around the current VR interfaces interaction capabilities. More specifically, while haptics, the sense of touch, is a major source of immersion in VR, stimulating it harmonically in virtual environments is still challenging. Indeed, interactions in VR were enabled for a long time through virtual metaphors and physical controllers, letting bare-hands interactions with believable haptic feedback out of the scope. Bare-hands interactions however enable easy-to-access virtual environments even for novice users, with interactions seamlessly resembling to the real world ones, such as direct manipulation [1]. In these regards, many implementations currently aim to let the user's hands unencumbered of handheld technologies while providing haptic feedback [2].

In this paper, we focus on **augmenting the exoskeleton class of haptic devices**. Apart from controllers, they are currently a widespread solution for providing force-feedback in VR, mainly for industry or training applications. Their feedback heavily focuses on the users' fingers, through either rigid parts [3] or strings [4]. However, current haptic exoskeleton gloves are still lacking a crucial manual sensory cue: the palmar contact feedback.

According to grasp and hand gestures taxonomies [5], [6], many interactions involve the palm: these are mainly referred to as *power grasps*, and are used for the exploration of planar surfaces or the manipulation of potentially large objects in 3D object manipulations [6].

This paper introduces a novel haptic approach for alleviating one of current exoskeletons limitations: the lack of palmar stimulation. We show how to augment a widespread and commercially available exoskeleton (*SenseGlove*) with a custom-made and 3D printed on-demand handheld for palmar contact. We draw inspiration from *Haptic Pivot* [7] to improve the haptic rendering of exoskeletons through palmar stimulation.

We present PalmEx's interaction design space, and provide a technical evaluation defining its interaction latency. A novel software implementation is shown to reduce the delay between the virtual-physical interactions below 0.5s. We empirically evaluate PalmEx's proposed design space in a user experience (n= 12) and demonstrate the benefits of a palmar contact augmenting an exoskeleton. Results show that PalmEx, instantiating palmar stimulation for exoskeletons, provides a significantly increased visuo-haptic consistency for various 3D object manipulations.

2 RELATED WORK

2.1 Exoskeletons Gloves for Haptic Rendering

Exoskeletons show two main benefits for VR applications: (a) they enable a thorough tracking of the users' gestures while (b) letting the users' hands free for *direct manipulation*, "the ability for a user to control objects in a virtual environment in a direct and natural way, much as objects are manipulated in the real world" [1]. Their designs enable various types of grasp types. From the classic grasp taxonomies (see Section 3), they can either enable pad opposition [8], palm opposition [3] or all of them [9] with force feedback from 7 to over a 100 N. While these are efficient to render

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- *This project has received funding from Inria (Associated Teams programme).*
- *E. Bouzbib and A. Lécuyer are with Inria, CNRS, Univ Rennes, IRISA – Rennes, France. E-mail:* {`name.surname`}`@inria.fr`
- *M. Teyssier is with Léonard de Vinci Pôle Universitaire, Research Center – Paris La Défense, France. E-mail:* {`name.surname`}`@devinci.fr`
- *C. Pacchierotti and T.Howard are with CNRS, Univ Rennes, Inria, IRISA – Rennes, France. E-mail:* {`name.surname`}`@irisa.fr`.

feedback over the fingers, none of these implementations focus on stimulating the palm. This is however a crucial area to render 3D object manipulation and their associated shape and kinesthetic force-feedback.

2.2 Palmar Stimulation in VR

Handheld devices stimulating the users' palms in VR have therefore been designed in these regards. Palmar contact enables size, shape and stiffness renderings, which can be simulated by 1.5D tangible interfaces [10], inflatable proxies [11], shape-changing handhelds [12] or wearables [13], [14], [15]. Their main limitation is that they are required to be held continuously within the hand. A promising perspective is to let the users' hands free and to integrate palmar contact through encountered-type devices [2], on-demand [7] or wearable interfaces [16].

2.3 Augmenting and Coupling Exoskeletons

Our approach aims to augment current exoskeletons with a tangible encountered-type interface. This augmentation of exoskeletons or wearables has already been investigated. Exoskeletons [17] and wearables [18] were augmented using Electro-Muscle Stimulation, which was shown to improve dexterity or impact perception. Similarly, wearables and exoskeletons were coupled with grounded [19] , cutaneous interfaces [20], or pseudo-haptics techniques [21].

In this paper, our focus is simple yet innovative: we focus on augmenting exoskeletons with a palmar contact, providing physical and kinesthetic shape and force-feedback.

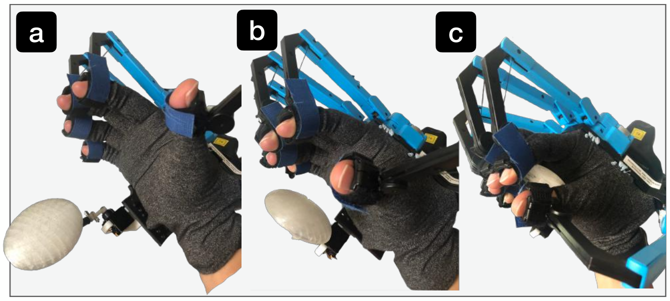

Fig. 1. (a) The user's palm is unencumbered prior to interaction. (b) The palmar interface goes towards her palm while the user starts gesturing a grasp. (c) When engaging the grasp, the user perceives force-feedback from both the exoskeleton *and* the palmar interface.

3 PALMEX: DESIGN SPACE

PalmEx's principle is to augment an exoskeleton with a physical tangible contact actuator in the palm area. We build upon grasp taxonomies to explicit PalmEx's design space.

3.1 Grasps

Grasping is task- and object-dependent (e.g. size, shape). Taxonomies differentiate two main types of grasps: *precision* and *power* grasps. In a *precision* grasp, the hand is "able to perform intrinsic movements" [5]. This is mostly performed through the fingertips, and with small scaled objects - compared to the average hand size. Exoskeletons are ideal for these types of grasps as they constrain the fingers.

A *power* grasp is defined as a "rigid relationship between the object and the hand" [5], [6]. This type of grasp is usually performed with the palm, and potentially large objects. As an example, previous palmar devices *Haptic Pivot* focused on the simulation of a contacting sphere, with two associated grasps (sphere 3/4 fingers). In comparison, PalmEx aims to widen this grasp design space to other objects and sizes from the taxonomies.

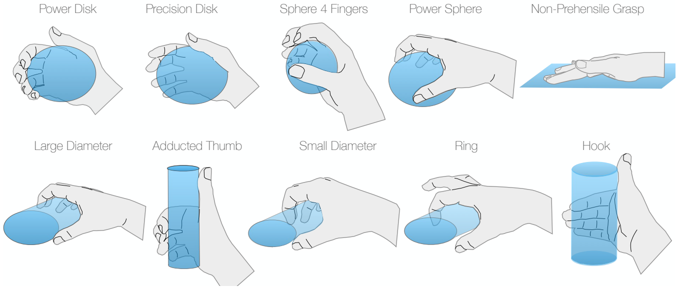

Fig. 2. Types of Grasps extracted from [5] and [6] and enabled with force-feedback with PalmEx's capabilities. PalmEx allows the manipulation of small, medium and large disks, cylinders and spheres. It also allows for non-prehensile grasps (touch of surfaces, hook).

Finally, there are also "non-prehensile" grasps defined by Cutkosky [22], where the hand acts as a unit, to perform "hook postures" and the touch of a surface.

Our approach consists in enabling all types of grasps proposed in the literature. We show in Figure 2 some examples of grasps allowed by PalmEx[1]: we propose the manipulation and exploration of (potentially large) disks, spheres, cylinders or surfaces. The palmar interface enhances interaction in the palm, while the exoskeleton constrains the fingers.

3.2 Interactions

We differentiate PalmEx's interaction design space in two categories: *static* and *dynamic*. They relate to the way PalmEx interacts with the user.

In a *static* interaction, PalmEx is fully engaged within the user's palm - its displacement is over (Figure 1 - c); while a *dynamic* interaction is enabled through PalmEx's actuation and dynamism (e.g. it bounces between Figure 1 - b and c).

3.2.1 *Static*

PalmEx encounters the user's palm when the virtual interaction occurs to provide force-feedback (see Figure 1). PalmEx enables to explore objects by **touching** them using the whole-hands. This exploration can be performed through non-prehensile grasps. On the contrary, prehensile grasps are enabled through **grasp** interactions - represented through complete taxonomies (see previous subsections). Users can also **pull**, **push** (literal displacement or push buttons) or **raise** objects while perceiving feedback within their palms and fingers.

3.2.2 *Dynamic*

PalmEx distance to the user's palm matches the distance between their virtual palms and the objects during the interaction. It provides different levels of force-feedback - it can touch the user's palm or push through it with a *continuous force interaction contact*. These variations allow for the perceptions of impacts, for instance with **catching** or **throwing** interactions (see Figure 3 - d). PalmEx also enables the users to **dribble** at different speeds and with balls of various weights - as the objects can be encountering

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[1] The names of the grasps are extracted from the taxonomies.

the users' palm with adaptive forces at contact. PalmEx also enables the users to **edit** objects and **mold** them as play doh (see Figure 3 - c), they can modify their overall structure [23]. Similarly, users can **palpate** objects: they can **deform** them (see Figure 3 - a), and feel a palpation when the virtual objects bounce back.

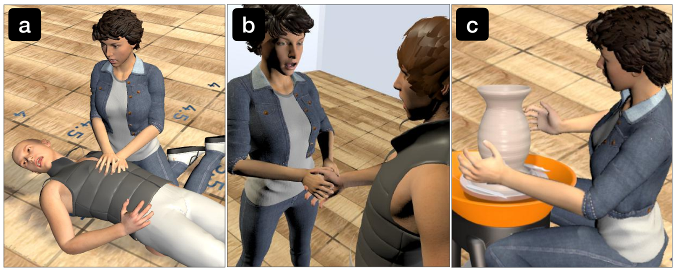

Fig. 3. Three potential scenarios involving PalmEx. (a) Medical training: An avatar is performing CPR training on another avatar. (b) Social touch: Avatars are shaking hands. (c) Leisure: The avatar is molding a vase.

4 APPLICATIONS

Using PalmEx's interaction design space, we envision three kinds of use-cases for PalmEx.

4.1 Medical Training

PalmEx could be used for medical training (Figure 3 - a). Using the dynamism of the encountered-type interface, PalmEx can be used for CardioPulmonary Resuscitation (CPR) training or medical palpation.

4.2 Social Touch

Using PalmEx, users can potentially receive or give social touch in VR. Users could either provide the interaction, by touching their friends shoulders or shaking their hands (Figure 3 - b); or receive the interaction, giving high-fives to virtual avatar friends. Some artificial skin [24] can be added to PalmEx's 3D printed ellipsoid, to provide users with even more believable social touch interaction.

4.3 Leisure & Sports

PalmEx can be used in a pottery scenario (Figure 3 - c) - in which users could feel the deformation of the mud, and modify it using their whole hands. This use-case involves an *edition* task [23] - which is still underexplored in virtual environments. We finally envision sport games or training using PalmEx. PalmEx could be used for hand-ball games: users could dribble prior to throwing a ball or practice gooalkeeping. PalmEx can also be used for racket games - using force within the palm, users could therefore perceive impacts when throwing balls; or for music (saxophone, trumpet), where the instrument is held within the palm and the fingers press the pistons.

5 IMPLEMENTATION

PalmEx is composed of (1) an exoskeleton, constraining the fingers and (2) an encountered-type interface on the palm.

5.1 Exoskeleton

We rely on the commercially available SenseGlove DK1 exoskeleton[2]. This exoskeleton glove relies on strings attached to the fingertips and is actuated with motors and friction brakes. Coin vibration motors are also integrated in the glove's rigid mechanical parts.

5.1.1 Hand Attachment

We adjusted the SenseGlove DK1 attachment technique and replaced the default velcro straps by a compression glove (Large size). This attachment keeps the exoskeleton over the user's hand and keeps the palm free of any contraption and available for interaction.

5.1.2 Tracking

We use the SenseGlove SDK to capture the user's finger phalanges positions and articulations; and we track the entire apparatus spatial location with a Vive Tracker Pro. Similarly to other exoskeletons (e.g. [4]), the SenseGlove SDK relies on an inverse kinematic model, which models the finger phalanges positions based on the extension of the strings. It also provides a hand pose database capturing when a grab interaction is about to occur.

5.1.3 Exoskeleton Software

The exoskeleton software relies on Unity3D for visualisation and physics. We added colliders to each virtual phalanx to enable collisions with virtual objects. This upgrade allows for (non-)prehensile user interactions and *game-initiated* interactions, where objects encounter the users' hands.

5.2 Palmar Contact

We designed a custom palmar contact hardware interface, inspired from *Haptic Pivot* [7] and *Weatavix* [25].

5.2.1 Interface Design Choices

We considered multiple technologies, such as pneumatic interfaces [11], motor-belt haptic systems [26] or a crank-slider mechanisms [20]. While these techniques seem efficient to provide haptic feedback, we decided upon the design of an active "on-demand" technology. We aimed for an on/off impact to highlight the interaction timestamp and balance the exoskeleton's haptic transparency [27] - this "phantom" effect which provides a continuous feedback due to the exoskeleton inner impedance and viscosity. Indeed, as the exoskeleton is constantly worn over the fingers, a resistance can be felt even though no force-feedback is provided. Reducing this effect was investigated in the design of exoskeletons - such as in Wolverine [8], where mass and inertia are considered as constraints and optimised in a light-scale custom exoskeleton. However, the investigation of such custom designs is out of scope of this paper - we aim to augment current high-end commercially available ones.

5.2.2 Mechanical Design

We decided to design a 3D printed ellipsoid for encountering the user's palm. We tested different heights and widths (from $5-11mm$ height, $70-85mm$ widths, $45-60mm$ length). The 3D ellipsoid is required to be ergonomic within the users' palm, and for them to be able to perceive both of flat (Figure 4 - a) or curved objects, either small (Figure 4 - b) or large (Figure 4 - c). This design prevents the perception of edges, as the curvy shape of the ellipsoid always encounters the palm first. We empirically chose a $10x55x75mm^3$ interface (Figure 4). This interface is 3D-printed, using PLA material, and weighs 11g; it is finally attached to a 3D-printed lever-arm connected to the motor.

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[2] www.senseglove.com

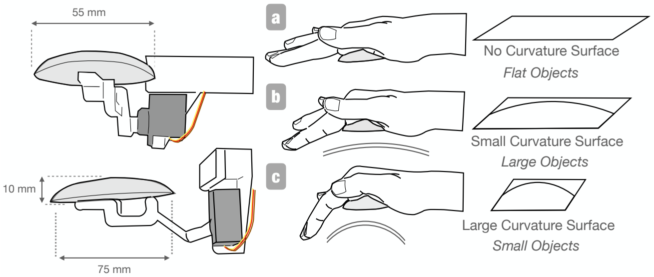

Fig. 4. Schematic of the custom-made palmar contact interface. A $10mm$ high half-ellipsoid is used to simulate a wide range of curvatures: (a) Flat; (b) Small curvature; (c) Large curvature.

5.2.3 Actuation and Control

Our palmar contact implementation relies on a servomotor. We used a Hitec 5065mg servomotor, as it has robust metal gears, and provides a $1.8kg.cm$ torque at $4.8V$. Its small size ($23.6 \times 11.6 \times 24mm^3$, weight = $12g$) facilitates its integration. Its speed specification is around $0.14"/60\deg$. We use a Pololu Micro Maestro 6-channel USB Servo Controller to control it in position with a 250 Hz serial communication. Prior to using the servomotor, we first define its working range. We define two extrema in its stroke: (1) when the interface is "out of reach" of any finger gesture; (2) when the interface is fully "engaged" (touching the SenseGlove plate). Its control is detailed in the Technical Evaluation (Section 6).

5.2.4 Force and Contact

We define two types of contact forces when the palmar interface touches the hand. The first contact force (≈ 0.30N) is used for *simple interaction* contacts, when the interface lightly touches the palm. The second contact force pushes through the palm and provides a higher force. We define it as a *continuous force interaction contact* (≈ 1.24N). This force is applied to simulate impacts objects within the palm. Forces can be provided between these two values, and are sufficient to render interactions.

5.2.5 Integration with the SenseGlove

We designed a 3D-printed holster to attach the servo and its controller board. This case is mechanically connected to the main SenseGlove plate. This plate is held within the previously discussed compression glove, which is finally sewn to the SenseGlove case (Figure 1).

6 TECHNICAL EVALUATION

The exoskeleton and palmar interface interact differently with the user's hand: one is continuously worn and pulls the users fingers (*SenseGlove*); the other one encounters and pushes on their palm (*Pivot*). These two stimulations occur from different directions - for them not to disrupt each other, it is hence important to have a good synchronisation at contact. We conducted a Technical Evaluation to (a) calibrate the servomotor and (b) propose a method to adjust its synchronisation as a function of the next intended interaction.

6.1 Calibration

We define two methods to calibrate the servomotor speed. The first one is based on the *time to contact*, the second one is based on the *next intended interaction speed*. We used the same experimental design for both of these methods.

6.1.1 Experimental Design

6.1.1.1 Procedure: We designed a virtual environment using Unity3D. We added a virtual object of interest - OOI (a sphere) - and assigned its position to the distance between the virtual hand and the palm. This distance represents the arc drawn by the servo during its displacement. We define a cycle to run, in which the servomotor (a) goes to being fully engaged (continuous force interaction contact position), (b) stops for 0.5s, (c) disengages itself (out of reach position), (d) waits for 0.5s (see Figure 6). The glove is not worn by users in this technical experiment.

6.1.1.2 Conditions: The Pololu Maestro board enables to change the servomotor speed and acceleration with units of $0.25\mu s/10ms$ (max 255 units). We tested 10 speeds and 10 accelerations: from 25 to 250 units, with an increment of 25. We run N = 10 cycles of each condition (10 SPEEDS × 10 ACCELERATIONS × 10 CYCLES).

6.1.1.3 Measures: In our virtual environment, we measured the speed of the virtual object (cm/s) and the time for the servomotor to finish its stroke (e.g. go through the full servomotor arc ($\approx 90°$).

6.1.2 Results

We first analysed the results per speed and accuracy, and noticed that the widest ranges (speed-wise) were reached when the acceleration matched the speed value. We therefore chose to rely on the diagonal values of our *speed × acceleration* matrix in the following results.

6.1.2.1 Speed (cm/s): We convert the servo speed units in cm/s (Figure 5 - Speed Calibration). This conversion is similar to a third order polynomial (R^2 = 0.99):

$$v_{virt} = f(v_{servo}) = p_0 v_{servo}^3 + p_1 v_{servo}^2 + p_2 v_{servo} + p_3 \quad (1)$$

This information is used to change the servomotor speed as a function of the users' hand speed, the object's speed, or both (see Section 6.2).

6.1.2.2 Time to Contact: The servomotor takes between 0.18s to 1.9s to be fully engaged. We fitted a third order polynomial to illustrate it, similar to Equation 6.1.2.1 (R^2 = 0.98) (Figure 5 - Time to Contact). The servo speed and acceleration can then be matched using this fitted equation, to encounter the user at t_c (time to contact).

6.1.3 Discussion

The "time to contact" calibration can be coupled with a *Jerk Model* [28] based on the user's hand gestures, predicting a future contact time stamp. Yet, this can create abrupt movements of the servomotor and increase the inertia of the system; ultimately altering the haptic transparency of the system (e.g. if the hand is at rest and suddenly interacts, with a predicted time to contact in 0.2s, this would activate the servomotor at almost full speed and cause some inertia). The jerk model - predicting time for contact - is more appropriately used for controlling interfaces which displacements are not altering the user experience (e.g. independent mobile platform). Similarly, while the servomotor speed can be modified as a function of the "interaction speed" (i.e. *the speed between the object of interest and the user's hand*), this command is always adjusted *after* a change of interaction speed. This calibration would hence improve the latency between the virtual and physical artefact, but a global latency would remain. We propose to intertwine the two calibrations to reduce the latency (Figure 5): we predict the time remaining to contact *prior* to interaction and adjust speed to optimise the servomotor displacements and reduce the time/position differences at contact.

6.2 Method: Intertwining Calibrations

According to our design space, the *interaction speed* depends on what/who initiates the interaction: it can either be (a) the user's hand speed, (b) the object's speed, (c) a combination of these two. We define the "virtual minimum distance", as the distance between the object's closest point from the virtual palm, and the virtual palm's closest point to the object (e.g. not between their centres *but* over their virtual boundaries). The *interaction speed* is therefore defined as the delta of virtual minimum distance during a given time (empirically defined as 30 frames, ≈ 0.6s).

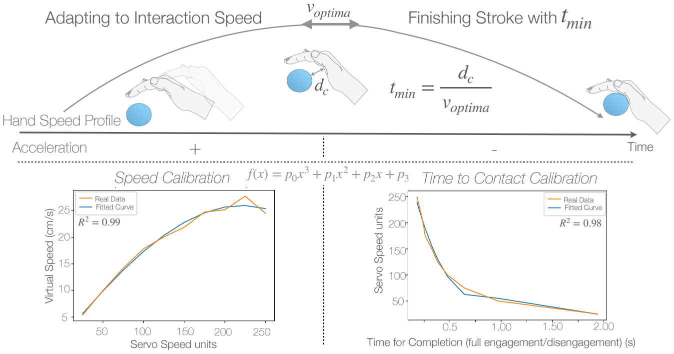

Fig. 5. Our method to enable the virtual/physical synchronisation. We first use the speed calibration to match the servo speed with the interaction speed. When the hand decelerates, we use the time to contact calibration for the servo to finish its stroke in the remaining time.

We also use the "time to contact" information to adjust the servomotor displacements *prior* to the virtual interaction. As the hand's speed usually decreases just prior grasping an object, we capture this deceleration timestamp, and calculate t_min as the "time lapse to contact". It is used as a threshold to command the servo to finish its stroke, as per Figure 5 - *Finishing Stroke*. The aim is for the interface to physically encounter the user's hand simultaneously with the virtual object of interest and the avatar hand interaction.

6.2.1 Experimental Design

6.2.1.1 Procedure and Conditions: We designed a virtual environment and cycles where the hand is moving towards a target at a given speed. The variable is the virtual hand speed on Unity3D. We tested N = 10 cycles of each speed between 2.0 and $8.0cm/s$ (increment of $1.0cm/s$).

6.2.1.2 Measures: We measure four key indicators: the time difference at t_c (Figure 6 - a), the position difference at d_c (in cm and in degrees) Figure 6 - b), the time difference when disengaging (t_d) (Figure 6 - c) and the position difference when disengaging (d_d) (Figure 6 - d). We also measure the speed at engagement (from t_{sH} to t_c) and disengagement (from t_{lH} to t_o).

6.2.2 Results

Our results are displayed in Table 1. The time difference between contact and servomotor engagement Δ_{te} is under $0.71s$ (std = $0.3s$). When the interaction speed is limited, the servomotor is synchronised correctly for the interaction to occur (Δ_{te} is below $0.5s$, $d_d < 4cm$, e.g. at $t_c + 0.5s$, the palmar interface is located within the palm).

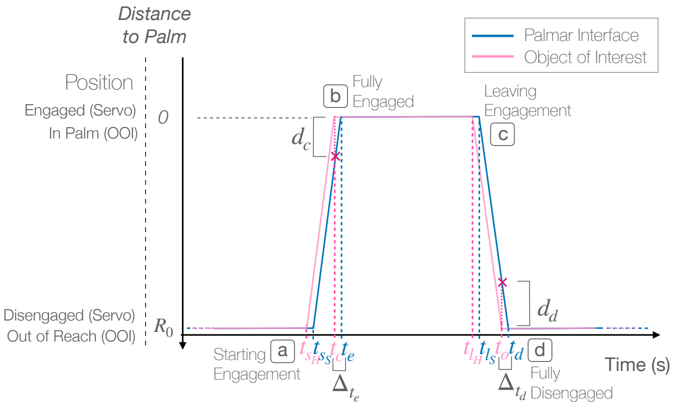

Fig. 6. A Technical Evaluation cycle, and the four key phases to analyse. (a) Starting: the Object of Interest (OOI) distance to the palm goes within reach at t_{sH}. The servo starts at t_{sS}. t_{sH} and t_{sS} should be as close as possible. (b) Fully Engaged: the OOI is in the user's palm. The distance d_c and Δ_{te}, difference of time at engagement (time of contact t_c - time of engagement t_e) are to minimise. (c) Leaving: the OOI leaves the palm position, at t_{lH}, and the servo follows at t_{sS}. Finally, (d) Fully Disengaged: the OOI is out of reach at t_o, followed by the servo at t_d. Δ_{td}, difference of time at disengagement, and d_d, distance between the object and the palmar interface, are to minimise.

	Time Engagement (s)	Position at Contact (cm)	Time Disengagement (s)	Position at Disengaged (cm)
Virtual Command Speed	Δ_{t_e} (s) (STD)	d_c (cm) (STD)	Δ_{t_d} (s) (STD)	d_d (cm) (STD)
2	0.21 (0.16)	1.28 (1.07)	0.08 (0.02)	0.52 (0.11)
3	0.40 (0.22)	3.21 (1,02)	0.21 (0.05)	1.75 (0.47)
4	0.51 (0.27)	4.17 (1.74)	0.46 (0.08)	4.26 (0.87)
5	0.75 (0.23)	6.08 (1.27)	0.72 (0.11)	8.09 (0.58)
6	0.60 (0.29)	6.19 (2.78)	0.76 (0.10)	8.69 (1.50)
7	0.64 (0.31)	5.89 (1.92)	0.82 (0.14)	8.75 (0.49)
8	0.71 (0.31)	6.71 (1.75)	0.81 (0.11)	8.99 (0.55)

TABLE 1
Results of our evaluation. As a function of the virtual speed command, we display time difference and distance at contact/fully disengagement.

6.2.3 Discussion

6.2.3.1 Scalability: Our approach can be applied for other types of "on-demand interfaces" and generalised for future generations of interfaces that could benefit from a palmar contact feedback: exoskeletons gloves, finger wearables etc. At a larger scale, our interface could benefit from a coupling with machine learning algorithms, to be adjusted optimally with the users' grasp gestures [29].

6.2.3.2 Simulation vs Real Users: The cycle was simulated as a virtual hand colliding with an OOI, and did not simulate the user's deceleration slope prior to interaction. We believe that the "time to contact" threshold strategy would be more effective in real user experiences. This was validated during the User Experience (Section 7) - where no synchronisation issue was noticed with real users.

6.2.3.3 Potential Speed Limitations: Using our fitted equation, we are limited to a maximum interaction speed of $29cm/s$. The curve is not fitted above, as we cannot send a higher signal to the servomotor. A mitigation strategy for this potential speed failure would reduce the user's hand speed and/or the object of interest speed, to a maximum of $29cm/s$. This solution ("visuo-proprioceptive illusion") is a common strategy for speed related limitations [2].

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7 USER EVALUATION

We conducted a user study to evaluate PalmEx's ability to cover grasps from Section 3. Our main hypotheses are that (1) PalmEx's approach provides more consistent feedback for (non-)prehensile grasping; (2) PalmEx is more effective for perceiving 3D manipulations than standalone exoskeleton or palmar - more effective than a control condition.

7.1 Participants

Twelve participants (6 M, 6 F), all right-handed, aged 24 to 36 (mean = 27, std = 4) volunteered for the experiment. Five participants were beginners in Virtual Reality, 4 were intermediate and 3 were experts.

7.2 Hardware

All participants wore the HTC Vive Cosmos HMD, PalmEx on their right hand (i.e. dominant hand) and a Vive controller in their left hand (to rate, change conditions etc).

7.3 Experiment Design

7.3.1 Procedure

Participants were first informed of the aim of the study, its duration (20 min), understanding their haptic perception while grasping. They were therefore asked to respect the objects virtual geometrical boundaries when interacting.

7.3.2 Tasks and Stimuli

The scene was designed on Unity3D. The tasks consisted in manipulating 3D objects and giving feedback about their physical consistency. The scenario was the following:

> *Emma enters the virtual environment and sits by a table. At each task, four virtual objects appear around the table. Emma manipulates the first object, and answers an affirmation using a virtual slider, corresponding its grade. She releases the object and makes the table turn. She manipulates the second object, rates it, releases it; etc. Emma may keep making the table turn to adjust her grades. The simulator stops after a total of 16 tasks.*

7.3.3 Conditions

We controlled a factor related to the physical interface in our experiments (Device) and one related to the objects (Shape). Participants performed the same Manipulation.

We considered four Devices: PalmEx, Palmar contact, Exoskeleton and Inactive. In PalmEx, both of the exoskeleton and the palmar interface are active; in Palmar contact, the exoskeleton is worn but passive, and the palmar interface is active; in Exoskeleton, the exoskeleton is active and the palmar interface remains inactive; in Inactive, both of the interfaces are worn but remain inactive. All Devices conditions are tested without changing the apparatus. We considered 4 Shapes: Sphere, Cylinder, Disk and Surface and 1 Manipulation: Grab (for prehensile objects) or Touch (for the surface). Their sizes were chosen according to the average hand size: $15cm$ for sphere diameters and surfaces, $8cm$ for cylinders heights and diameters and disks diameters, $5cm$ for disk height. These objects represent the basic primitives involving the whole hand, and their associated grasps (see Section 3): both precision and power disks grasps can be performed in our user experience.

7.3.4 Design

We used a within-subject design. The appearance of each condition was randomized within the blocks. Each object (Device condition) appeared randomly on the table. Each participant performed 4 blocks, and tested 64 conditions (e.g. 4 Devices × 4 Shapes × 1 Manipulation × 4 Blocks). The global experimental design was: 12 Participants × 64 Conditions = 768 Trials.

7.3.5 Measures

For each trial, participants had to provide feedback on their perception using a 7-point Likert-scale to rate the sentence: *"I feel the* Shape[3] *in my hand."* (*1: Completely Disagree*; *7: Completely Agree*). We recorded each configuration and associated rates.

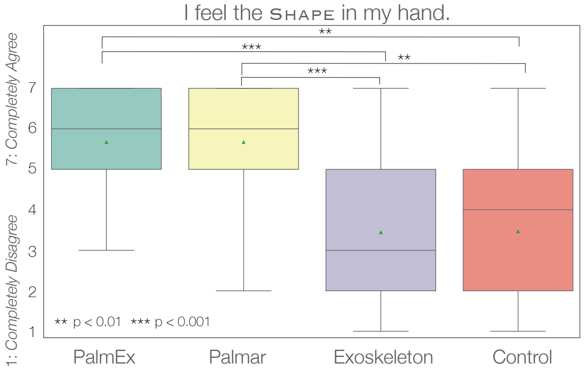

Fig. 7. Boxplot of our experiment results: "I feel the Shape in my hand" on a 7-point Likert scale, 1: *Completely Disagree*; 7: *Completely Agree*. Stars show the significance of the results (** $p < 0.01$, *** $p < 0.001$).

7.4 Quantitative Results

We analyzed the results by conducting a 2-way repeated measures ANOVA, to define the effects of Devices, Shapes and Blocks. Posthocs pairwise T-tests with Bonferroni-corrected p-values are applied to display the results. Ninety-five Confidence Intervals are noted as *95-CI* in the following.

7.4.1 Global Effects

We found a significant effect for Devices ($F_{(3,99)}$ = 22.8, p < 0.001; η^2 = 0.5); no effect for Shapes, and a small effect on Blocks ($F_{(3,99)}$ = 2.4, p < 0.1, η^2 = 0.01).

7.4.2 Device *Effect (Figure 7)*

Our results show that participants felt the virtual object in their hand using either PalmEx (mean = 5.67, 95-CI = 0.15), or Palmar (mean = 5.67, 95-CI = 0.16) compared to Exoskeleton (mean = 3.44, 95-CI = 0.23) or Inactive condition (mean = 3.46, 95-CI = 0.24). Effects were found between PalmEx or Palmar and Exoskeleton (p < 0.001) or Inactive (p < 0.01), but no effect was found between PalmEx and Palmar or Exoskeleton and Inactive.

7.4.3 Block *Effect*

We studied the training block effect while using the devices. We found an effect for Exoskeleton, between the first (mean = 4.0, 95-CI = 0.49) and last block (mean = 2.9, 95-CI = 0.4) (p $<$ 0.001). A **significant effect between PalmEx (mean = 5.9, 95-CI = 0.28) and Palmar condition (mean = 5.5, 95-CI = 0.39)** occurred during the last block (p < 0.05) using Tukey pairwise tests with Bonferroni correction.

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[3] Shape was replaced with the configuration's associated object.

7.5 Qualitative Feedback

7.5.1 Consistency of Exoskeleton Rendering

Three participants spontaneously mentioned that the exoskeleton pulling their fingers made them feel like puppets - P11 mentioned that she struggled understanding how the tension in her fingers were simulating the manipulated objects. She added it was "easier to apprehend the palmar contact, as the feedback [was] consistent with [her] vision". We emphasize that participants **did** perceive an illusory force-feedback when the exoskeleton was inactive - yet felt the active EXOSKELETON was too sudden and gruff.

7.5.2 Favourite Shapes

Four participants mentioned that the cylinders were their favourite objects to grab, with no regards to their visuo-haptic consistency. P6 mentioned that he could potentially see lots of use-cases using our interface, such as assembly training, or games involving swords for instance.

7.6 Summary & Discussion

We summarize our results and open a discussion on perspectives thanks to PalmEx's results.

7.6.1 Palmar Stimulation

Our experience **validates our first hypothesis** and shows that palmar stimulation for 3D object manipulation is important, no matter if the exoskeleton is active or not. From the qualitative feedback, we noted that the manipulation of cylinders (*power grasps*) was preferred.

7.6.2 Pseudo-Haptics Enhance Inactive Exoskeletons?

Our results highlight the importance of our first hypothesis but **revoke our second hypothesis**. They are indeed showing only a small effect on the last block between PALMEX and PALMAR conditions and no noticeable effect between EXOSKELETON and INACTIVE conditions among blocks. We believe this is due to the internal viscosity of current haptic exoskeletons gloves. While their hand tracking is accurate, and proven to augment presence compared to classic controllers [30], this viscosity coupled with a "physicalized" hand (no object penetration) is here shown to be preferred for 3D object manipulation. This almost *pseudo-haptics* effect is usually proven to alter perception, but we did not expect it to alter the exoskeleton rendering. This opens up an interesting discussion regarding 1) the effectiveness of pseudo-haptics coupled with active physical haptic interfaces, 2) current high-end exoskeletons weight, inertia, resistance and viscosity specifications.

7.7 Comparative Discussion

We highlight the advantages of the combination of palmar and exoskeleton in the following.

7.7.1 Exoskeleton vs Inactive

We emphasize here how the exoskeleton is required for the rendering and explain the differences between these two conditions. The fingers are receiving a force-feedback from the exoskeleton - whether it is active or not. The inner resistance and viscosity of the device coupled with visual cues provides an *illusory sensation* that the device actively pulls on the fingers. The exoskeleton is what enables the precision grasp to be performed, and truly enhances the rendering enabled by *Haptic Pivot* for instance.

7.7.2 Palmar vs Inactive

These two DEVICE conditions reflect on the combination of our palmar interface and the exoskeleton. The exoskeleton is inactive in both these conditions, yet participants perceived a force-feedback due to the previously-evoked pseudo-effect. We show the benefit of the palmar interface coupled with the (inactive) exoskeleton: it significantly increases the grasps consistency.

7.7.3 PalmEx vs Palmar

Finally, the advantages of having the exoskeleton *active* and the palmar interface is that it is better perceived that the *inactive* exoskeleton with the palmar interface. Indeed, the last block showed a significant effect between PALMEX and PALMAR. While participants qualitatively evoked the unexpected tension from EXOSKELETON compared to INACTIVE, we show that when it is correctly synchronized with simultaneous stimulation on the palm, the perception for grasp consistency and exoskeleton efficiency is thus enhanced.

8 PERSPECTIVES & FUTURE WORK

PalmEx highlighted the importance of the palmar contact to enhance 3D object manipulation. We envision two main perspectives in PalmEx's line of work.

8.1 Degrees of Freedom and Usability

Our interface with a degree of freedom (DoF) was sufficient to simulate most grasps from taxonomies, with large, medium and small, curved or completely flat objects. We plan on confirming this finding in an assembly training user experience with completion time and accuracy measurements, representing a viable application for PalmEx. We also believe that adding the rotation of the palmar interface as additional DoF could provide the users with more complex haptic stimulation in their palms. This subsequent DoF could potentially add an edge perception feature. In the same line of observations, interfaces with numerous DoFs such as *X-rings* [12] could be adapted to be "on-demand" and integrated in PalmEx.

8.2 Pseudo-Haptics and Lighter Exoskeletons

Our results opened an interesting research question regarding the coupling of *Pseudo-Haptics* and *Active Haptic Interfaces*. As future work, we propose to investigate coupling lighter exoskeletons (such as [8]) to enable a potentially more *transparent* [27] perception and verify the effectiveness of exoskeleton gloves with and without pseudo-haptics.

9 CONCLUSION

We proposed PalmEx, a novel approach to improve 3D object manipulation in VR. PalmEx consists in upgrading haptic exoskeleton gloves with an actuated palmar interface., and offers a wide design space, built upon current taxonomies. PalmEx was described through its ergonomic design, its control and actuation, and evaluated for its delay at interaction and *virtual:physical* synchronisation. We conducted a user evaluation (n = 12) demonstrating the benefits of palmar contact for augmenting exoskeletons' haptic feedback. Taken together, our results promote the use of palmar contact and pave the way to novel generations of haptic exoskeletons gloves.

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REFERENCES

[1] S. Bryson, "Direct Manipulation in Virtual Reality," in *Visualization Handbook*. Elsevier, 2005, pp. 413–430. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/B978012387582250023X

[2] E. Bouzbib and G. Bailly, ""Let's Meet and Work it Out": Understanding and Mitigating Encountered-Type of Haptic Devices Failure Modes in VR," in *VR 2022 - IEEE Conference on Virtual Reality*. Christchurch, New Zealand: IEEE, Mar. 2022, pp. 1–10. [Online]. Available: https://hal.archives-ouvertes.fr/hal-03548113

[3] M. Bouzit, G. Popescu, G. Burdea, and R. Boian, "The Rutgers Master II-ND force feedback glove," in *Proceedings 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. HAPTICS 2002*. Orlando, FL, USA: IEEE Comput. Soc, 2002, pp. 145–152. [Online]. Available: http://ieeexplore.ieee.org/document/998952/

[4] C. Fang, Y. Zhang, M. Dworman, and C. Harrison, "Wireality: Enabling Complex Tangible Geometries in Virtual Reality with Worn Multi-String Haptics," *CHI 2020*, p. 10, 2020.

[5] T. Feix, J. Romero, H.-B. Schmiedmayer, A. M. Dollar, and D. Kragic, "The GRASP Taxonomy of Human Grasp Types," *IEEE Transactions on Human-Machine Systems*, vol. 46, no. 1, pp. 66–77, Feb. 2016. [Online]. Available: http://ieeexplore.ieee.org/document/7243327/

[6] M. R. Cutkosky, "On grasp choice, grasp models, and the design of hands for manufacturing tasks," *IEEE Transactions on Robotics and Automation*, vol. 5, no. 3, pp. 269–279, Jun. 1989.

[7] R. Kovacs, E. Ofek, M. Gonzalez Franco, A. F. Siu, S. Marwecki, C. Holz, and M. Sinclair, "Haptic PIVOT: On-Demand Handhelds in VR," in *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*, ser. UIST '20. New York, NY, USA: Association for Computing Machinery, Oct. 2020, pp. 1046–1059. [Online]. Available: http://doi.org/10.1145/3379337.3415854

[8] I. Choi, E. W. Hawkes, D. L. Christensen, C. J. Ploch, and S. Follmer, "Wolverine: A wearable haptic interface for grasping in virtual reality," in *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. Daejeon, South Korea: IEEE, Oct. 2016, pp. 986–993. [Online]. Available: http://ieeexplore.ieee.org/document/7759169/

[9] J. Blake and H. Gurocak, "Haptic Glove With MR Brakes for Virtual Reality," *IEEE/ASME Transactions on Mechatronics*, 2009.

[10] S. Yoshida, Y. Sun, and H. Kuzuoka, "PoCoPo: Handheld Pin-based Shape Display for Haptic Rendering in Virtual Reality," in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. Honolulu HI USA: ACM, Apr. 2020, pp. 1–13. [Online]. Available: https://dl.acm.org/doi/10.1145/3313831.3376358

[11] S.-Y. Teng, T.-S. Kuo, C. Wang, C.-h. Chiang, D.-Y. Huang, L. Chan, and B.-Y. Chen, "PuPoP: Pop-up Prop on Palm for Virtual Reality," in *The 31st Annual ACM Symposium on User Interface Software and Technology - UIST '18*. Berlin, Germany: ACM Press, 2018, pp. 5–17. [Online]. Available: http://dl.acm.org/citation.cfm?doid=3242587.3242628

[12] E. J. Gonzalez, E. Ofek, M. Gonzalez-Franco, and M. Sinclair, "X-Rings: A Hand-mounted 360° Shape Display for Grasping in Virtual Reality," in *The 34th Annual ACM Symposium on User Interface Software and Technology*. Virtual Event USA: ACM, Oct. 2021, pp. 732–742. [Online]. Available: https://dl.acm.org/doi/10.1145/3472749.3474782

[13] B. Son and J. Park, "Tactile Sensitivity to Distributed Patterns in a Palm," in *Proceedings of the 20th ACM International Conference on Multimodal Interaction*, Boulder CO USA, Oct. 2018, pp. 486–491.

[14] K. Minamizawa, S. Kamuro, N. Kawakami, and S. Tachi, "A Palm-Worn Haptic Display for Bimanual Operations in Virtual Environments," in *Haptics: Perception, Devices and Scenarios*, M. Ferre, Ed. Berlin, Heidelberg: Springer Berlin Heidelberg, 2008, vol. 5024, pp. 458–463, iSSN: 0302-9743, 1611-3349 Series Title: Lecture Notes in Computer Science. [Online]. Available: http://link.springer.com/10.1007/978-3-540-69057-3_59

[15] M. Dragusanu, A. Villani, D. Prattichizzo, and M. Malvezzi, "Design of a Wearable Haptic Device for Hand Palm Cutaneous Feedback," *Frontiers in Robotics and AI*, vol. 8, p. 706627, Sep. 2021. [Online]. Available: https://www.frontiersin.org/articles/10.3389/frobt.2021.706627/full

[16] D. Trinitatova and D. Tsetserukou, "Touchvr: A wearable haptic interface for vr aimed at delivering multi-modal stimuli at the user's palm," in *SIGGRAPH Asia 2019 XR*, ser. SA '19. New York, NY, USA: Association for Computing Machinery, 2019, p. 42–43. [Online]. Available: https://doi.org/10.1145/3355355.3361896

[17] R. Nith, S.-Y. Teng, P. Li, Y. Tao, and P. Lopes, "DextrEMS: Increasing Dexterity in Electrical Muscle Stimulation by Combining it with Brakes," in *The 34th Annual ACM Symposium on User Interface Software and Technology*. Virtual Event USA: ACM, Oct. 2021, pp. 414–430. [Online]. Available: https://dl.acm.org/doi/10.1145/3472749.3474759

[18] P. Lopes, A. Ion, and P. Baudisch, "Impacto: Simulating Physical Impact by Combining Tactile Stimulation with Electrical Muscle Stimulation," in *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology - UIST '15*. Daegu, Kyungpook, Republic of Korea: ACM Press, 2015, pp. 11–19. [Online]. Available: http://dl.acm.org/citation.cfm?doid=2807442.2807443

[19] A. Steed, S. Friston, V. Pawar, and D. Swapp, "Docking Haptics: Extending the Reach of Haptics by Dynamic Combinations of Grounded and Worn Devices," *arXiv:2002.06093 [cs]*, Feb. 2020, arXiv: 2002.06093. [Online]. Available: http://arxiv.org/abs/2002.06093

[20] B. Son and J. Park, "Haptic Feedback to the Palm and Fingers for Improved Tactile Perception of Large Objects," in *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*. Berlin Germany: ACM, Oct. 2018, pp. 757–763. [Online]. Available: https://dl.acm.org/doi/10.1145/3242587.3242656

[21] M. Achibet, A. Girard, A. Talvas, M. Marchal, and A. Lecuyer, "Elastic-Arm: Human-scale passive haptic feedback for augmenting interaction and perception in virtual environments," in *2015 IEEE Virtual Reality (VR)*. Arles, Camargue, Provence, France: IEEE, Mar. 2015, pp. 63–68. [Online]. Available: http://ieeexplore.ieee.org/document/7223325/

[22] M. R. Cutkosky and R. D. Howe, "Human Grasp Choice and Robotic Grasp Analysis," in *Dextrous Robot Hands*, S. T. Venkataraman and T. Iberall, Eds. New York, NY: Springer New York, 1990, pp. 5–31. [Online]. Available: http://link.springer.com/10.1007/978-1-4613-8974-3_1

[23] E. Bouzbib, G. Bailly, S. Haliyo, and P. Frey, ""Can I Touch This?": Survey of Virtual Reality Interactions via Haptic Solutions," in *32e Conférence Francophone sur l'Interaction Homme-Machine (IHM '20.21), April 13–16, 2021, Virtual Event, France*, Apr. 2021. [Online]. Available: https://hal.archives-ouvertes.fr/hal-03122267

[24] M. Teyssier, G. Bailly, C. Pelachaud, E. Lecolinet, A. Conn, and A. Roudaut, "Skin-On Interfaces: A Bio-Driven Approach for Artificial Skin Design to Cover Interactive Devices," in *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. New Orleans LA USA: ACM, Oct. 2019, pp. 307–322. [Online]. Available: https://dl.acm.org/doi/10.1145/3332165.3347943

[25] X. de Tinguy, T. Howard, C. Pacchierotti, M. Marchal, and A. Lécuyer, "WeATaViX: WEarable Actuated TAngibles for VIrtual reality eXperiences," p. 9, 2020.

[26] M. Aggravi, F. Pause, P. R. Giordano, and C. Pacchierotti, "Design and Evaluation of a Wearable Haptic Device for Skin Stretch, Pressure, and Vibrotactile Stimuli," *IEEE Robotics and Automation Letters*, vol. 3, no. 3, pp. 2166–2173, Jul. 2018.

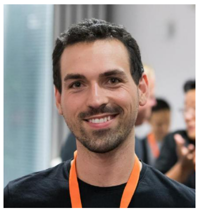
[27] D. A. Lawrence and L. Y. Pao, "Quantitative experimental analysis of transparency and stability in haptic interfaces," *Proc. Fifth Annual Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pp. 441–449, 1996.

[28] M. Bratt, C. Smith, and H. I. Christensen, "Minimum jerk based prediction of user actions for a ball catching task," in *2007 IEEE/RSJ International Conference on Intelligent Robots and Systems*. San Diego, CA, USA: IEEE, Oct. 2007, pp. 2710–2716. [Online]. Available: http://ieeexplore.ieee.org/document/4398989/

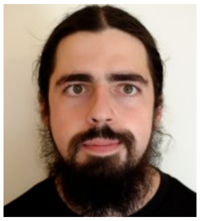
[29] M. Salvato, N. Heravi, A. M. Okamura, and J. Bohg, "Predicting Hand-Object Interaction for Improved Haptic Feedback in Mixed Reality," *IEEE Robotics and Automation Letters*, pp. 1–1, 2022, conference Name: IEEE Robotics and Automation Letters.

[30] H. S. Moon, G. Orr, and M. Jeon, "Hand Tracking with Vibrotactile Feedback Enhanced Presence, Engagement, Usability, and Performance in a Virtual Reality Rhythm Game," *International Journal of Human–Computer Interaction*, Jun. 2022.

Elodie Bouzbib is a postdoctorate researcher at Inria Rennes, France. She obtained a PhD from Sorbonne Université in Computer Science/Human Computer Interaction in 2021, for which she received the prize of 2022 Best Multidisciplinary PhD thesis from AFIHM. Her main research areas are HCI, Virtual Reality, Haptics and Robotics. She mainly prototypes artefacts to stimulate haptics in VR.



Marc Teyssier is Principal Investigator of the "Resilient Futures" research group at the De Vinci Innovation Center (Paris, France). His research in HCI and Design focuses on how technology impacts human interactions and behaviour and proposes alternatives to traditional devices using radical and critical design or Low-Tech and Bio-Fabrication methodologies.



Thomas Howard is a post-doctoral fellow with INSA Rennes at IRISA and Inria Rennes, France. He defended his PhD in robotics at Sorbonne Université in Paris in 2016, on the topic of haptic feedback for assisting in minimally invasive surgical procedures. His main research interests are haptic feedback technologies for rich multisensory virtual reality interactions.

Claudio Pacchierotti is a tenured researcher at CNRS-IRISA in Rennes, France, since 2016. He was previously a postdoctoral researcher at the Italian Institute of Technology, Genova, Italy. Pacchierotti earned his PhD at the University of Siena in 2014. Pacchierotti received the 2014 EuroHaptics Best PhD Thesis Award and the 2022 CNRS Bronze Medal. He is Senior Chair of the IEEE Technical Committee on Haptics and Secretary of the Eurohaptics Society.

Anatole Lécuyer is director of research and head of Hybrid team at Inria Rennes, France. His resarch interests are in virtual/augmented reality, haptic interaction, 3D user interfaces, and brain-computer interfaces. Anatole Lécuyer obtained the IEEE VGTC Technical Achievement Award in Virtual/Augmented Reality in 2019, and was inducted in the IEEE Virtual Reality Academy in 2022.