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DOI:
10.1145/3731406.3734977

Publication date:
2025

Document Version
Peer reviewed version

Link to publication

Citation for pulished version (HARVARD):
Villarreal-Narvaez, S, Septon, T & Dumas, B 2025, 'Designing Touch-Based Gestures for Thigh-Worn Wearable Device in Passenger-Focused Vehicular XR Environments', Paper presented at EICS 2025: 17th ACM SIGCHI Symposium on Engineering Interactive Computing Systems, Trier, Germany, 23/06/25 - 27/06/25. https://doi.org/10.1145/3731406.3734977

Designing Touch-Based Gestures for Thigh-Worn Wearable Device in Passenger-Focused Vehicular XR Environments

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Fig. 1. A participant proposing a gesture on our prototype during the study, alongside their view in the virtual environment.

With the rapid expansion of extended reality (XR) technologies in vehicular contexts, there is a growing need for innovative interaction methods that enhance user experience without compromising safety. In a research project, we explored the potential of a thigh-worn wearable device that allows passengers to interact with the onboard system and operate a roof-mounted surveillance camera. This includes actions such as navigating menus, selecting items, controlling media playback, and adjusting camera orientation, zoom, or recording. We conducted a Gesture Elicitation Study (GES) in a simulated vehicular XR environment with 24 referents, where 21 participants ($N = 21$) interacted with our prototype, ThighTouchI. This empirical study identified 79 unique gestures from 504 proposals, revealing that users favored ThighTouchI as a pad for selection tasks, using single-finger gestures for simple actions and multi-finger gestures for complex tasks. Additionally, a consensus gesture set was derived, and mapping of the tactile surface showed that 88.7% of the gestures were proposed in the central area. Participants utilized different zones of the touch surface depending on the referent, underscoring its ergonomic importance.

CCS Concepts: • **Human-centered computing** → **Haptic devices**; **Gestural input**; **User studies**.

Additional Key Words and Phrases: Touch/Haptic/Pointing/Gesture, Gesture Elicitation Study, Virtual/Augmented Reality, Thigh Wearable, in-Vehicle

ACM Reference Format:

Santiago Villarreal-Narvaez, Thibaut Septon, and Bruno Dumas. 2025. Designing Touch-Based Gestures for Thigh-Worn Wearable Device in Passenger-Focused Vehicular XR Environments. In *Companion of the 17th ACM SIGCHI Symposium on Engineering Interactive*

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Computing Systems (EICS Companion '25), June 23–27, 2025, Trier, Germany. ACM, New York, NY, USA, 16 pages. https://doi.org/1XXXXXXX.XXXXXXX

1 Introduction

The increasing interest in eXtended Reality (XR) has led to the development of new interaction methods for wearable devices [8, 48, 50]. While touch-based interactions work well on smartphones and tablets, adapting these for XR devices in confined spaces, such as vehicles, poses significant challenges [36]. Gesture vocabulary design has been a key area in HCI research aimed at creating more intuitive and user-friendly interactions [61]. These vocabularies can be developed through expert-led, user-led, or data-driven methods [66]. User-centred design tends to result in gesture vocabularies that target users find more learnable, memorable, and discoverable compared to expert-centred designs [39, 66]. The user elicitation method established by Wobbrock et al. [63] is extensively utilized for generating user-defined gesture vocabularies across various devices, applications, environments, and contexts of use [11, 56, 57].

As part of a research project, we were tasked with developing a prototype for passenger interaction in an XR vehicular scenario. We identified touch gestures as a promising interaction method for this context. In this work, we introduce ThighTouchI, a thigh-worn wearable prototype designed for interaction with the vehicle's onboard system and a roof-mounted camera. To guide the design of our gesture interactions, we conducted a Gesture Elicitation Study (GES) in a simulated vehicular XR environment to uncover user-defined touch-based gestures. Our contribution is a consensus gesture set, which, along with the analysis of empirical results from 21 participants interacting with 24 referents, generated 504 gesture proposals. This paper addresses two research questions (RQ) and three hypotheses (H):

*RQ*1 Does a curved, thigh-worn tactile surface influence the gestures proposed by participants compared to a traditional flat touch surface?
*H*1 The curved surface influences the proposed gestures.
*H*2 The thigh-worn location influences the design and characteristics of user-proposed gestures.
*RQ*2 Can users effectively operate the device without visual feedback?
*H*3 Proprioceptive feedback enables users to locate and interact with the device effectively.

2 Related Work

A comprehensive understanding of current research on Touch interaction, gesture interaction, GES, and thigh-mounted device interaction from XR environments is crucial for this study:

XR is a term widely used in the industry to describe immersive technologies, including Augmented Reality (AR) and Virtual Reality (VR) [1, 30]. It aligns with what is commonly referred to as Mixed Reality (MR) in the literature, as proposed by Milgram and Kishino [38]. XR presents new opportunities and challenges for user interaction, especially when incorporated into wearable devices. These devices aim to enhance XR experiences, making them more immersive and accessible while necessitating innovative input methods that are both intuitive and practical across various real-world settings [8, 48, 50].

Touch and Gesture Interaction in XR, touch and gesture-based interaction is crucial for intuitively manipulating virtual content in XR environments [47]. Advancements in wearables, such as smart glasses [19, 24, 52] and touchpads [23, 33, 53], offer new avenues for integrating touch and gesture controls into AR [41]. Studies have explored combining touch interaction with head movements [42], yielding promising user preference and effectiveness results. BodyTouch [10] have investigated eye-free, body-based touch interactions using on-body and near-body methods, offering valuable insights into touch accuracy and user preferences for body-part touch interfaces, particularly in VR. The choice between single-finger and multi-touch gestures depends on the task and user needs. Single-finger gestures are preferred for simple interactions due to their ease of use, while multi-touch gestures offer greater versatility for complex tasks requiring precise control [25, 44, 46].

Regarding **VR interaction within confined spaces** like car seating, *FingerMapper* [54] has demonstrated the potential of mapping finger motions onto virtual arms to reduce physical movement. *Seated-WIP* [9] introduces a footstep-based locomotion technique for seated VR users, leveraging forefoot and rearfoot stepping to simulate walking in confined spaces. *Gunslinger* [32] uses thigh-mounted sensors to track hand and finger movements for mid-air interactions, but with large displays.

Thomas et al. [53] and Harrison and Faste [14] highlight the potential of the **Front Thigh** as a touchable surface for interaction. The works of Heller et al. [15] and Harrison and Faste [14] analyze the pose (standing, sitting, and walking) using the thigh as a touchable surface, while Hu et al. [20] and Zielasko and Riecke [67] point out that sitting could be more comfortable for interacting with Head-Mounted Displays (HMDs). In **MR scenarios**, various methods for thigh-based interaction have been explored. *e.g., STAT* [16] investigates using a smartphone screen worn on the thigh for text entry in HMDs, while *LapTouch* Mi et al. [37] explores using the lap as a touch interface for seated VR/AR interaction. *FabriTouch* [15] integrates touch-sensitive fabric into wearable devices on the thigh, enabling basic gestures even on a flexible surface. The study by Schramm et al. [51] focuses on selection techniques using gaze and combinations with a device button and hand pointing with gesture confirmation in moving vehicles.

Regarding **GES**, these methodologies are commonly used to identify end-user gestures for interacting with different technologies [57, 62]. Most studies have focused on hand gestures, such as mid-air gestures [2, 3, 18, 58, 59], touch gestures on surfaces [27, 29, 60, 64], and device manipulation [12, 35, 43, 68]. However, there is a noticeable gap in research regarding gestures performed directly on the skin or specific body parts. Recent reviews [11, 56] underscore the growing significance of XR [5, 13, 28, 45] or in-vehicle [7, 17, 21, 22, 31, 34, 40] contexts in gesture research. Yet, none have examined a curved, thigh-worn touch interface for vehicle passengers in XR environments. Our work fills this gap by introducing ThighTouchI and deriving a consensus gesture set through a GES.

3 Methodology: Gesture Elicitation Study

In our case study, we examined a scenario where a user is seated in the passenger seat of a vehicle designed for surveillance tasks. This vehicle features various onboard functionalities and a roof-mounted camera with 360-degree horizontal coverage. Such vehicles are commonly employed to monitor borders, important public locations, tourist locations, or private security. As the initial step of our investigation, we developed a prototype intended to be worn on the thigh by a vehicle passenger (see Section 3.1). We focused on touch-based gesture interaction as a technique for our wearable device. Consequently, we conducted a Gesture Elicitation Study to collect user input and establish a consensus on touch gestures for the device's intended functionalities.

3.1 Our prototype: ThighTouchI

The *design inspiration* for our prototype came from the attire of combat airplane pilots, who often have a pocket with a transparent cover on their thigh to store maps, manuals, or mission objectives. This practical solution for quick access to important information in confined spaces played a key role in shaping our design. We envisioned a wearable device that could serve a similar purpose, providing users with an intuitive and easily accessible touch interface directly on their thighs. The front thigh area offers ample space and is optimal for high-precision inputs [14, 53]. It consists of two components, see Figure 2a:

The leg strap component, made of elastic black fabric, snugly fits around the user's thigh and has Velcro straps sewn around to attach the *touch surface component.*

The touch surface component (Figure 2b) is also made of black fabric with red accents and houses two compartments. One of these compartments is intended for the "GT-TF-XTM10.1L-1" touch foil (size 10 inches) from GreenTouch. This flexible touch foil is **transparent and compatible with curved surfaces**; it can detect up to 10 simultaneous points of pressure. It connects via USB to a Raspberry Pi Zero 2 W and is powered by a 2500 mAh battery, secured with custom-fit elastics in the other compartment. It is worth noting that a server is running on the Raspberry Pi, allowing any application that wishes to use it to connect wirelessly via the WebSocket protocol.

Additionally, the electronic components and touch foil can be easily removed to machine wash the fabric components, and the touch foil can be cleaned with monitor cleaning clothes. A document or map can be stored beneath the transparent touch foil, allowing users to interact with the physical information by touching different areas of the foil. The fabrics are designed to be similar to athletic wear, making them suitable for everyday use and washable if needed.

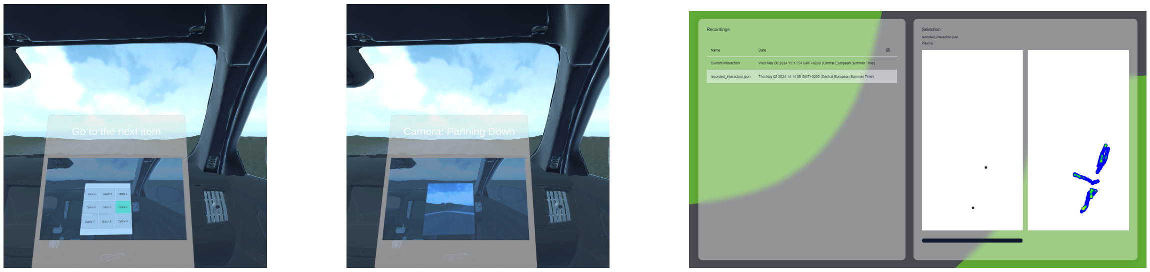
(a) ThighTouchI components (b) ThighTouchI electronic

Fig. 2. Introducing ThighTouchI

3.2 Referents

In the original GES [63], a referent is defined as any action, command, or task in the study in which participants are asked to propose gestures. We defined a set of referents (see Table 1). Although the referents are inspired by existing literature [7, 34, 40, 65], they have been customized for our case study.

We used a virtual panel positioned in front of the vehicle's passenger seat to illustrate these referents. This virtual panel projected a looping video that demonstrated the transition of each referent within an interface. The interface was specifically designed for the test, and participants were informed that it was not a final version but a tool used solely to illustrate the referents (see Figures 3a, 3b).



(a) Referent *R*4. (b) Referent *R*12. (c) Contact coordinates captured by the prototype

Fig. 3. Participant's point of view for two referents and the gesture's captured coordinates.

Table 1. List of referents defined for our GES.

Id.	Referent	Description
*R*1	Open/close Menu	Opening or closing the main menu
*R*2	Select an item	Selecting an item from the menu
*R*3	Go to the previous item	Navigating to the previous item
*R*4	Go to the next item	Navigating to the next item
*R*5	Accept/confirm an option	Confirming a selected option
*R*6	Cancel/Reject an option	Canceling or rejecting a selected option
*R*7	Camera: On/Off	Turning the camera on or off
*R*8	Camera: Switch mode	Changing the camera mode (thermal, night, normal vision)
*R*9	Camera: Panning left	Moving the camera view to the left
*R*10	Camera: Panning right	Moving the camera view to the right
*R*11	Camera: Panning up	Moving the camera view up (only when zoomed in)
*R*12	Camera: Panning down	Moving the camera view down (only when zoomed in)
*R*13	Camera: Zoom in	Zooming in the camera view
*R*14	Camera: Zoom out	Zooming out the camera view
*R*15	Camera: Return to the initial position	Resetting the camera to its initial position
*R*16	Camera: Record	Starting or stopping a recording
*R*17	Camera: Select Object	Marking an object (*e.g.,* a vehicle or person) for automatic tracking
*R*18	Play music	Initiating music playback
*R*19	Pause/Resume music	Pausing or resuming music playback
*R*20	Stop music	Stopping music playback
*R*21	Volume up	Increasing the volume
*R*22	Volume down	Decreasing the volume
*R*23	Take a call	Answering a call
*R*24	Hang up a call	Ending a call

3.3 Participants

A total of twenty-one volunteer ($N = 21$) participants were recruited through various methods, including email and personal invitations. This sample included 15 men and 6 women, with no participants identifying as other or non-binary. The participants' ages ranged from 23 to 38 years, with a mean age of 28.57 ($SD = 4.39$). They came from various fields, such as law, computer science, education, math, IT, and management. One participant was left-handed, and none was ambidextrous. The participants reported high usage of computers ($Avg = 6.86$, $SD = 0.48$, $M = 7$) and smartphones

(Avg = 6.67, SD = 0.66, M = 7), as well as touch surfaces (Avg = 5.57, SD = 2.16, M = 7). They reported infrequent use of XR headsets (Avg = 1.67, SD = 1.43, M = 1) and Kinect (Avg = 1.19, SD = 0.40, M = 1). The majority of participants considered tablets and smartphones as touch surfaces.

3.4 Setup and Apparatus

The study was conducted in person within a laboratory. During the experiment, each participant was placed in a chair. ThighTouchI was placed on the thigh of the user's dominant hand to facilitate interaction. We used Meta Quest 3 to simulate an XR environment where participants could visualize a virtual vehicle's interior and exterior. This virtual environment was developed using Unity and featured two cars, with the participant seated in the passenger seat of one. We used a PC to record the contact coordinates from our prototype, which allowed the experimenter to view the gesture in real time on the screen and to capture the gesture visually (see Figure 3c). Additionally, a camera recorded a video of the participant executing their proposed gesture, with the camera positioned at the participant's thigh to maintain anonymity, see Figure 1.

3.5 Protocol and Variables

The experiment began with two experimenters welcoming the participant to the laboratory. For this study, we based our methodology on the original Gesture Elicitation Study proposed by Wolbrock *et al.* [64] and adapted it following the suggestions proposed by Williams and Ortega [62], Villarreal-Narvaez et al. [56] and Cheng et al. [11] for the GES process. The study was designed to last around 40 minutes. Participants were informed that they could stop participating if they felt uncomfortable or encountered any issues during the study. We divided the study into three phases: Pre-test Phase, Test Phase, and Post-test Phase.

Pre-test Phase, During this phase, participants were asked to complete a consent form to register their information, ensuring anonymity, as well as a demographic questionnaire including questions about the frequency of usage of devices such as computers, smartphones, and touch surface. Participants were briefed on the purpose of a GES, the setup of the laboratory equipment, the XR environment, and an introduction to our prototype. Subsequently, participants were fitted with the prototype and the Meta Quest 3 and were given a minute to adapt.

Test Phase, Once participants had put on the Meta Quest 3, they could no longer see their real surroundings, including the thigh-worn prototype. This ensured that all touch gestures were guided by proprioception rather than direct visual feedback from the device. The study involved 24 different referents (see Table 1) presented to participants in a random order [55]. Each referent was introduced one at a time, allowing participants time to reflect on and propose gestures they found most suitable. One of the experimenters controlled the test system, launching each referent and ensuring that the participant could view the related video. When the participant understood the referent, the video panel disappeared. Participants indicated their readiness by verbally stating "ok" when they had selected a preferred gesture. They had the option to repeat the gesture if desired. After recording the gesture proposal, participants rated its *goodness-of-fit, complexity,* and *memorability*. The experimenter then launched the next referent after the participant responded to the final variable.

Post-test Phase, Upon completion of presenting all referents, the participant's prototype and Quest 3 were removed. Finally, participants were asked to complete a questionnaire consisting of two parts: a SUS questionnaire [6] and an additional questionnaire including open-ended questions for participants to express their negative and positive opinions.

Four ***variables*** were collected in the Test Phase. *Thinking time* refers to the duration participants took to propose a gesture for the reference presented. *Goodness of Fit* was used to evaluate how well participants believed their gesture aligned with the referent, rated on a scale from 1 to 10. Additionally, participants rated their gesture's *Complexity* on a scale from 1 to 10, indicating the extent to which they perceived it as challenging to produce or inducing fatigue. Lastly, *Memorability* represented a rating from 1 to 10, indicating how easily participants believed the gesture could be remembered and reproduced.

3.6 Results and Discussion

This section presents the analysis of the data collected during our GES:

3.6.1 Variables. We recorded four variables (see Section 3.5) per referent and by participants. We then ran a descriptive statistical analysis to evaluate how they correlate with each other. The calculated Pearson correlation coefficient between each variable is available in Table 2. The supplementary material also provides raw data and box plots for each variable.

The participants took an average of 19.23 seconds ($SD = 1.85$ seconds) to propose gestures. They viewed their proposed gestures as a good-of-fit ($Avg = 7.66$, $SD = 1.85$), memorable ($Avg = 7.78$, $SD = 1.68$) and not complex ($Avg = 2.47$, $SD = 1.68$). Moreover, we can observe that the *complexity* variable is inversely proportional to the *goodness-of-fit* and *memorability* variables, while the lattes are positively proportional. As one could expect, this means that the more the proposed gesture is classified as complex, the less it is likely to be considered memorable and fitting. On the other hand, the more a gesture is fitting, the more likely the participant will find it easy to remember. When comparing how the measured *thinking-time* is correlated to other variables, we can observe that the more a participant took time to think of a gesture, the more it would be considered complex and, therefore, less likely appropriate and memorable. Referents R7, R8, R15, and R16 received the most marginal values, with significant variability.

Table 2. Pearson correlation coefficients for each variable.

	Memorability	Complexity	Thinking Time
Goodness-of-fit	r =0.9041 p =1.381e-09	r =-0.6788 p =0.0002658	r =-0.8931 p =4.361e-09
Memorability		r =0.7266 p =5.8e-05	r =0.8056 p =2.039e-06
Complexity			r =0.6437 p =0.0006886

3.6.2 Agreement Rate. Vatavu and Wobbrock [55] introduced this measure among participants to propose a gesture class for a referent. We used AGATe, a tool described in the same article, to compute values for each referent, displayed in ascending order in Figure 4.

The results show significant variability in participants' consensus regarding the most intuitive gestures for different referents. The data reveals that the actions with the highest agreement were R14 ("Camera: Zoom out") and R13 ("Camera: Zoom in"), reaching agreement levels of 0.652 and 0.733, respectively. In contrast, actions such as R7 ("Camera: On/Off") and R15 ("Camera: Return to the initial position") had the lowest levels of agreement, with values of 0.024 and 0.01, respectively, reflecting more significant divergence in gesture preferences. On average, the Agreement Rate among participants was *medium*, with a value of 0.181, highlighting the diversity of interpretations regarding the most appropriate gestures for the various actions proposed in our GES. Of the 24 referents analyzed, 41.67% (10/24) exhibited *low agreement* ($\leq$ 0.100), indicating a significant variation in participants' gesture choices for these referents. Meanwhile, 37.5% (9/24) of the referents showed *medium agreement* (0.100 - 0.300). A smaller portion, 12.5% (3/24), reached a *high agreement* (0.300 - 0.500). Lastly, only 8.33% (2/24) of the referents achieved *very high agreement*(> 0.500), underscoring the relatively few instances where participants overwhelmingly favored the same gesture for a given referent.

While developing the study with participants, we expected that the *Agreement Rate* for referents $R23$ and $R24$ would be 1, as participants commonly proposed gestures used on smartphones. However, two participants suggested the opposite gestures, *e.i.,* they used the pinch-in gesture for zooming in and the pinch-out gesture for zooming out.

3.6.3 *Touched Areas.*

To generate the heatmap in Figure 5 and analyze how participants interacted with ThighTouchI, we utilized the contact coordinates captured by our prototype (see Section 3.4) and video footage from each session to confirm and provide context for each touch event. This heatmap shows the frequency of touch in each area, with red indicating the highest intensity and blue indicating the lowest intensity. The numbers in the heatmap represent the percentage of participants who touched each area. Users prefer the central area (88.7%) of the touch surface. However, it also shows that users use the opposite areas equally. *e.g.,* the bottom left zone has the same percentage (1.8%) as the bottom right.

Figure 5 demonstrates that users tend to perform certain actions on a touch foil in specific directions. *e.g.,* they prefer the left or bottom-left region for making a call and the right or bottom-right side for ending a call. Even when using the same touch area, users use different gestures for different actions, such as using opposite directions to adjust the volume. This behavior may be influenced by real-world habits, study demonstrations, or the smartphone's touchscreen design.

The spatial placement of icons and options on the interface significantly influenced participants' gestures. For example, participants tended to swipe from the left when the "Take a call" icon was on the left. The same pattern was observed for "Hang up a call" and "accepting" or "canceling" options.

3.6.4 *System Usability Scale Questionnaire.*

According to Bangor et al. [4], Our average SUS score of 68.93 ($SD = 15.52$) is *"okay"*, close to *"good"*. These results are promising, considering the novelty of HMDs, our prototype, and its touch and gesture interaction technique for the participants.

3.6.5 *Gesture set and classification.*

504 gestures were collected, involving 21 participants across 24 referents ($21 * 24 = 504$). A senior researcher with expertise in GES and a PhD student classified these gestures. Through careful analysis of participants' notes, videos, and audio recordings of their think-aloud comments, 79 unique gestures were identified and categorized (a complete list is available in our supplementary materials). The number of fingers used primarily distinguished these gestures; for instance, "Swipe up" with one finger was categorized separately from "Swipe up" with two fingers. However, no distinction was made based on which specific fingers were used—*e.g.,* whether a participant performed the "Swipe up with two fingers" gesture using the index and middle fingers or the middle and ring fingers.

The consensus gestures (see Figure 4) identified for each referent reveal a pattern of repetition, with specific gestures used across multiple referents due to their contextual relevance. For instance, the "Tap with one finger" gesture was consistently selected for actions such as accepting or confirming an option ($R5$), playing music ($R18$), pausing/resuming music ($R19$), stopping music ($R20$), and taking a call ($R23$). This repetition likely stems from participants' familiarity with these gestures in similar contexts on smartphones or other touch devices. Additionally, the "Swipe left with one finger" gesture was used for several camera-related actions, such as switching modes ($R8$), panning left ($R9$), and hanging up a call ($R24$), reflecting its intuitive application in navigation tasks. Similarly, gestures like "Swipe up with three fingers" ($R1$) for opening/closing the menu and "Pinch in/out with two fingers" for zooming in and out ($R13$, $R14$) are standard interactions commonly associated with touchscreens, particularly in camera and media contexts. Many

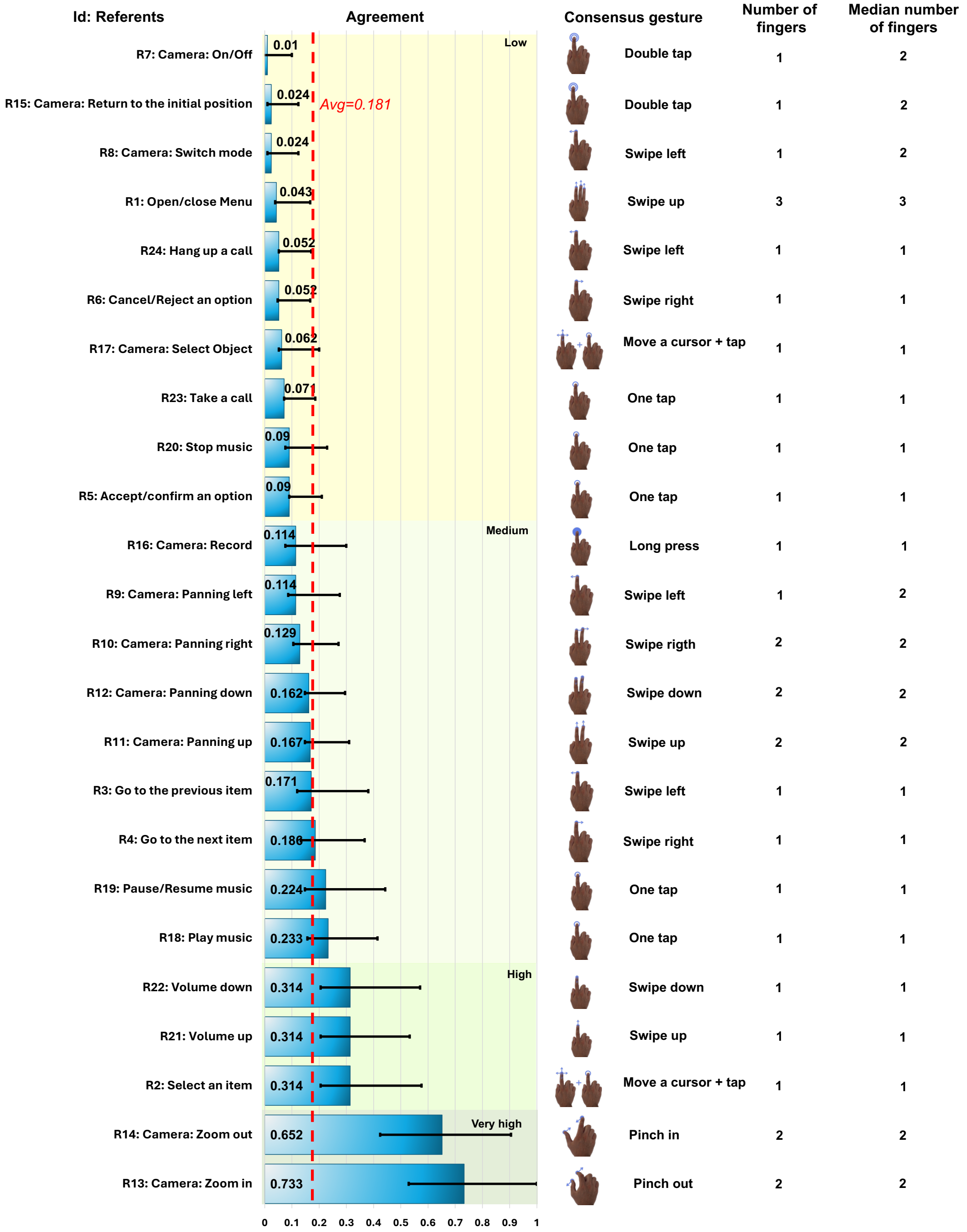


Fig. 4. Agreement Rate, consensus gesture and the median number of proposed fingers: Referents list, The Agreement Rate (Ar) value (Average-Avg, interpretation and the error bars show a confidence interval of 95%) ordered in ascending order calculated in AGATe [55], the consensus gesture with the number of fingers and the median number of proposed fingers per referent.

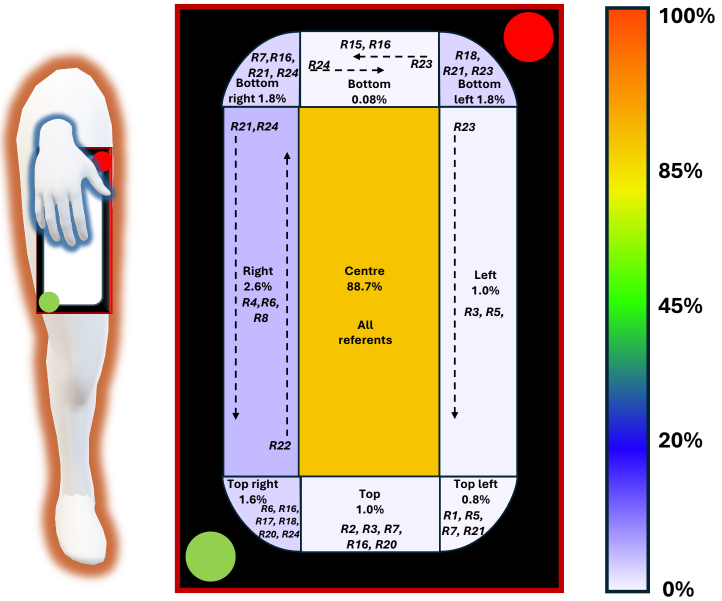


Fig. 5. Zone-divided heatmap of touched areas and Mapping of areas for referents

participants commented that their gesture choices were influenced by their interactions with smartphone touchscreens or headphones, where gestures like double-tap are frequently used for tasks like pausing music or focusing the camera.

Fingers use and number, Participants mostly used a single finger for simple referents but used two fingers for camera zooming. More complex tasks like panning showed varying finger usage, indicating a balance between precision and ease of use. Opening or closing the menu saw diverse preferences, with some using three or more fingers (see Figure 4).

The distribution of finger usage shows that single-finger gestures are the most intuitive, with approximately 56.7% of participants using just one finger for most actions, such as selecting items and confirming options. Two-finger gestures were the next most common, accounting for 29% of gestures, particularly for zooming and some camera panning tasks. Three-finger gestures were less frequent, used by 8.3% of participants, often for more complex actions like opening menus. Only 5.6% of gestures involved four or more fingers, reserved for distinct operations. This pattern suggests that the number of fingers involved increases as task complexity increases. This finding is consistent with research conducted by Kin et al. [25]. Two participants suggested unconventional gestures for *R*8 (Camera: Switch mode): "Tap with the fist" and "Tap with the edge of an open hand, like a karate chop." These gestures stand out because they involve no finger contact, representing a unique approach among the participants. The lack of finger involvement, at 0.4%, indicates an exploration beyond the typical finger-based gestures, possibly influenced by more physical actions.

Participants commonly used their index fingers for single-finger gestures, but Participant *P*16 preferred using the thumb. Two-finger swiping gestures typically involve the index and middle fingers, while gestures mimicking manipulation of a physical object, such as rotating a handle, use the index finger and thumb. Three-finger swipes involved the index, middle, and ring fingers, and manipulation gestures used the thumb, index, and middle fingers. Although 20 participants used their index finger and thumb for the pinch gesture, *P*15 used her index and middle fingers, and the think-aloud confirmed it as a pinch. Notably, Participant *P*17 was the only one who used both hands for camera gestures, forming a square with each hand’s index finger and thumb and sliding with four contact points.

Gestures by Nature and Form [64], The results are shown in Figure 6. Regarding the Gesture Nature, Physical gestures dominated, representing 74% of the total. This reflects a strong tendency for participants to use gestures that mimic physical interactions with real objects. In Gesture Form, most gestures (69%) were classified as dynamic, indicating that most gestures involved movement or change rather than being performed in a static location.

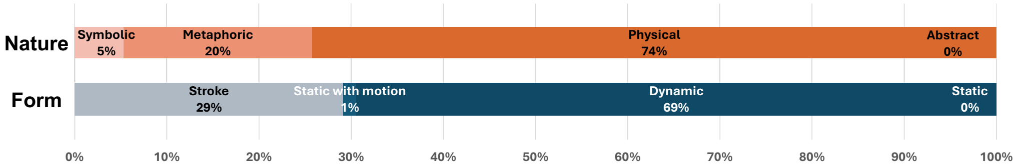


Fig. 6. Classification of gesture by *nature* and *form*

Finally, we discuss also each hypothesis:

H1. The consensus gesture set resembles those reported in gesture elicitation studies on flat surfaces [27, 29, 60, 64] and commonly used on smartphones and tablets. However, our data indicate that the curved, thigh-worn tactile surface significantly influences interaction patterns. Figure 5 shows that 88.7% of gestures occurred in the central area, suggesting that the curvature directs users to specific zones. This pattern contrasts with the more scattered touch interactions typically observed in the literature, providing partial support for *H1*.

H2. The results also indicate that ThighTouchI ’s wearable nature is crucial in gesture selection. Participants relied on proprioceptive feedback (evidenced by relatively low *complexity* ratings and short *thinking times*) to produce gestures accurately without visual cues, suggesting that the thigh’s location facilitates intuitive gesture design and execution. These results clearly support *H2*.

H3.Usability measures (including *SUS* scores and high *goodness-of-fit* ratings) indicate that participants could operate the device effectively without relying on visual feedback. Only one out of 21 participants asked during the *Test Phase*, "Where is the touch surface?" and that participant immediately located it. When later asked if they generally found it difficult to identify the tactile surface, they stated that they did not. This consistency in gesture proposals across various referents further supports *H3*, confirming that proprioceptive cues are adequate for interaction with the prototype.

4 Limitations and future work

A common limitation in gesture elicitation studies, including ours, is relying on participants familiar with touch devices, such as smartphones or computers. This group includes students, researchers, and administrative staff, which is typical for these studies. While this allows comparison with existing literature, future studies should diversify the participant pool to include those less familiar with technology, children, and older adults, offering insights into gesture intuitiveness and usability across demographics.

Additionally, our experimental setup involved participants seated on a standard chair rather than a car seat. This difference in seating ergonomics might have influenced the natural interaction patterns and the distribution of touch areas on the thigh. Moreover, we did not vary the sitting posture; in real vehicular environments, users may adopt different postures (*e.g.*, leaning forward, reclined), which could lead to a preference for different regions of the thigh for touch input.

Future work will focus on expanding the interaction capabilities of our prototype. We plan to integrate and explore additional techniques, such as "Gaze to Point and Swipe to Execute" and "Interaction with Physical Information" (*e.g.,* by placing a physical map beneath the tactile foil), to complement the touch-based gestures captured in this study. We are also planning a user experience (UX) evaluation to assess the "Gaze to Point and Swipe to Execute" technique alongside social acceptability [49] and wearable comfort metrics [26] for ThighTouchI. Finally, we aim to conduct a comprehensive study similar to that of Schramm et al. [51] to evaluate all three interaction techniques in real-world vehicular XR environments, incorporating more realistic seating conditions and varied sitting postures.

5 Conclusions

This study demonstrates that a curved, thigh-worn touch prototype shows potential as a medium for capturing user-defined gestures in in-vehicle XR interactions for passengers. Our Gesture Elicitation Study collected 504 proposals from 21 participants, with 88.7% of touches concentrated in the central area, indicating that the device's curvature guides users toward specific interaction zones. Furthermore, the usability (*SUS* score) measures and qualitative data reveal that participants can consistently interact without visual feedback, relying on proprioceptive cues. Although the consensus gesture set resembles those found on flat surfaces, the unique touch patterns observed here provide valuable insights for designing ergonomic, body-worn interfaces in vehicular XR environments. Future work will expand these findings through real-world evaluations and the inclusion of additional interaction modalities. All code, JSON files, schematics, questionnaires, a video demo, and results are available in a publicly accessible repository[1], ensuring transparency and facilitating further research in this area.

Acknowledgments

The authors thank the anonymous reviewers for their helpful suggestions that enhanced this manuscript. They also appreciate the gesture elicitation study participants and Madame Fabienne Sevrin's assistance with the garment prototype. Stance in preparing the garment for the prototype.

Santiago Villarreal-Narvaez, Thibaut Septon and Bruno Dumas are supported by the OPTIMIS project by Pôle MecaTech under Grant no. 8564.

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accepted April 25, 2025