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RESEARCH PAPER

Evaluation of Passive Haptic Proxies for Virtual Scalpel Interaction in Medical Simulations with Virtual Reality

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Abstract. Previous studies on tactile guides in VR focused on generic tasks and diverse audiences, leaving gaps in understanding their role in specialized medical simulations. This study investigates how physical properties—weight, shape, texture, thermal sensation, and grip—affect the user experience and Sense of Agency (SoA) in a surgical context. Thirteen participants with prior surgical training manipulated four objects representing virtual scalpels, allowing a controlled evaluation of physical–virtual correspondence and ergonomic comfort. The results suggest that even moderate mismatches between physical and virtual objects can generate discomfort and reduce perceived control, highlighting the critical role of ergonomic and kinesthetic factors in precise tasks. Compared to previous works, these findings suggest that assessing multiple perceptual and motor variables in a specialized audience provides deeper insights into optimizing VR-based surgical training and designing effective tactile guidance strategies.

Keywords: Haptic, Proxy Haptic, Medical Simulation, Virtual Reality

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1 Introduction

Virtual Reality (VR) has transformed training practices across various fields, particularly in healthcare. Its ability to create realistic and controlled simulations allows students and professionals to perform complex procedures, such as surgeries and suturing, without exposing patients to risks [Gani *et al.*, 2022]. Traditional surgical training relies heavily on the use of cadavers, live animals, or patients, which imposes logistical, financial, and ethical limitations. These factors reinforce the need for innovative approaches that offer realistic, repeatable, and safe practice opportunities [Sanfilippo *et al.*, 2025].

Among these approaches, the use of haptic devices in VR scenarios stands out, being essential for training involving psychomotor skills. Tactile interaction and force perception play an important role in creating more complete learning experiences. Sanfilippo *et al.* [2025] emphasize that integrating multiple sensory channels (vision, hearing, and touch) contributes to a multimodal immersion capable of enhancing understanding and skill development. Multimodal immersion also influences the Sense of Agency (SoA), understood as the user's subjective perception of voluntarily controlling their actions and the resulting effects. This sense is strongly associated with the feeling of presence and often serves as a central criterion for sustaining the illusion of actually being in the virtual environment [Jeunet *et al.*, 2018].

Despite their potential, the adoption of haptic systems faces significant barriers, including high cost, mobility restrictions, variations in feedback types (tactile or force), size, weight, and grip, among other factors (Pacchierotti *et al.* [2017]). These challenges range from computational limitations and hardware difficulties to issues related to human perceptual behavior and the logistics of using physical objects.

The literature explores several limitations associated with integrating haptic feedback into VR. Tong *et al.* [2023] note that fixed devices provide high force fidelity but restrict mobility and are expensive. Wearable solutions, such as gloves and haptic accessories, aim to increase freedom of movement but tend to become bulky and heavy, potentially causing fatigue during use. Talhan *et al.* [2023] further highlight that actuators require complex structures, add rigidity to the system, and demand careful calibration, which compromises scalability and comfort.

Alternatively, several studies investigate the use of Substitutional Reality [Simeone *et al.*, 2015], which involves using everyday physical objects as "tactile guides" or "haptic proxies", mapped to corresponding virtual objects. While promising, this approach also presents challenges. Nilsson *et al.* [2021] argue that in rich virtual environments, maintaining a physical correspondence for each virtual object implies high computational cost. As scenario complexity increases, the need for multiple physical objects with distinct properties becomes impractical. To avoid this problem, Auda *et al.* [2021] propose using the same physical object to represent several virtual objects. This strategy, however, requires haptic retargeting techniques or visuo-haptic illusions to adjust the user's perception, demanding sophisticated algorithms and precise control of the sensory experience.

The fidelity of the correspondence between physical and virtual objects is essential to preserve immersion, but is difficult to achieve it accurately. Tinguy *et al.* [2019] observed that discrepancies in properties such as size and shape, or mass distribution, can weaken the haptic illusion and affect performance. Using a light object to represent something heavy, for example, creates sensory conflict that can break the experience.

Another set of challenges involves tracking and co-location. Nilsson *et al.* [2021] emphasize that the virtual object must maintain strict spatial alignment with its physical counterpart. If the user attempts to interact with a virtual object and finds no physical support, or conversely touches the real object sooner than expected, immersion is immediately compromised. Wee *et al.* [2021] reinforce that the synchronization between the hand, the real object, and the virtual object must be precise, as misalignments directly affect the experience. These limitations are exacerbated by occlusion issues. Hanzaki and Boulanger [2020] point out that cameras and tracking sensors frequently lose sight of the object when hands cover it, which is critical in medical simulations or complex interactions. Furthermore, Greensdale *et al.* [2023] mention that the latency between real movement and its update in the virtual environment can compromise realism and generate discomfort.

Given this scenario, this article presents the development and evaluation process of a VR experiment focused on medical simulation, with an emphasis on Substitutional Reality. The study explored a low-cost alternative based on the use of everyday objects to simulate the handling of a scalpel, investigating how shape, weight, temperature, texture, and grip influence the user's perception.

2 Haptic Interaction and the Use of Tactile Guides in Virtual Reality

Interaction in VR environments allows the user not only to observe but also to act within the virtual space. For this interaction to be intuitive and effective, the system must provide sensory feedback consistent with the user's actions. In the context of medical simulations, tactile feedback is particularly important for the development of proprioception, that is, the ability to perceive the position and movement of one's own body [Weber *et al.*, 2021]. Wee *et al.* [2021] highlight that the presence of haptic interactions contributes to virtual objects acquiring more consistent physical properties, enhancing the user experience.

Haptic devices are traditionally responsible for providing this type of sensory feedback. However, force feedback systems, such as CyberGrasp (https://www.cyberglovesystems.com/cybergrasp), are costly, bulky, and restrict user mobility due to the need for complex infrastructure [Pacchierotti *et al.*, 2017]. The Geomagic Touch, although widely used, faces similar limitations and still presents constraints related to its handle design (https://br.3dsystems.com/haptics-devices/touch). More accessible solutions, such as wearable devices, often provide only vibratory feedback, which is insufficient to represent the complexity of surgical procedures [Tong *et al.*, 2023].

Given these limitations, a promising alternative is the use of passive tactile guides, in which real physical objects are associated with corresponding virtual objects. Simeone *et al.* [2015] introduced the concept of Substitutional Reality, in which real objects could be mapped to distinct virtual objects, as long as they maintain functional correspondence. This strategy aims on enriching tactile interaction without relying on specialized and high-cost haptic devices. The Substitutional Reality can be defined as the construction of Virtual Environments (VEs) in which a physical object is paired with a virtual version, allowing for some degree of discrepancy between the two. The objective is to enable physical elements to provide tangibility to virtual objects, enhancing the sense of presence. In this approach, the user manipulates the real object, perceiving its weight, shape, and texture, while visually interacting with its virtual representation. Figure 1 illustrates this principle: a real object is tracked by the system and replaced by a virtual model, allowing the user to see the virtual object while physically perceiving its real counterpart.

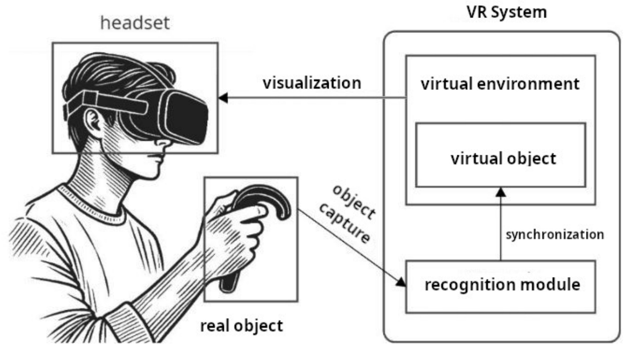

Figure 1. Schematic of tactile guide usage in a virtual reality system.

Based on experimental studies, Simeone *et al.* [2015] investigated the tolerable limits of discrepancies before the illusion is compromised, analyzing factors such as suspension of disbelief, ease of interaction, and engagement. The authors found that, although exact replicas provide higher credibility, moderate incompatibilities - particularly aesthetic or functional - may be acceptable. Furthermore, substitute objects with physical characteristics similar to those of the virtual object maintain engagement levels comparable to those achieved with faithful replicas.

Subsequent studies have sought to improve the correspondence between physical and virtual objects. Hettiarachchi and Wigdor [2016] proposed a system capable of scanning the environment in real time to identify physical objects whose geometric characteristics match those of virtual objects. Kobeisse and Holmquist [2022], in turn, compared different interfaces and concluded that even a generic object, such as a wooden cylinder, can provide a more immersive experience than purely visual interfaces or flat markers, reinforcing tactile guides as a viable and economical alternative.

Greensdale *et al.* [2023] investigated the use of household objects as physical props to control virtual objects in first-person augmented reality games, aiming to understand user preferences and the factors that affect immersion. The results suggest that the objects used should have shapes and sizes similar to the virtual object, be comfortable to handle, and have a weight distribution consistent with user expectations.

In the context of medical simulation, Hanzaki and Boulanger [2020] proposed the use of a haptic proxy to simulate the manipulation of a syringe in a virtual environment. In a pilot study with 12 participants, the authors observed good acceptance of the technology, indicating its potential in medical training. The findings suggest that the haptic proxy provides a more realistic training experience, although at a cost of slower task execution. However, the study highlights that the experience could be more accurate if the shape of the virtual object were more aligned with the physical object, an aspect also discussed by Kwon *et al.* [2009], Simeone *et al.* [2015] and Tinguy *et al.* [2019].

The integration of haptic feedback also influences the SoA, as reported by Rückert *et al.* [2024], who developed adaptive tool replicas with haptic feedback for use in VR. Tests indicated a significant increase in both presence and sense of agency during virtual assembly tasks, when compared to conventional controllers.

The studies presented provide the foundation for the current work: exploring the simplicity of tactile guides to develop an accessible medical simulation experiment, prioritizing correspondence between the physical properties of the real object, such as weight, shape, and grip, and the functionality of the virtual instrument, considering multimodal immersion as a means of enhance the user's SoA. The following section discusses the relationship between the use of tactile guides and the SoA, a central element for evaluating the quality of immersive environments.

3 Tactile Interaction and its Relationship to the Sense of Agency

The sense of presence in VR environments, understood simply as the illusion of being physically present in the simulated space, refers to user's psychological displacement from their physical environment to the virtual one. Rückert *et al.* [2024] note that a sense of presence directly influences performance in immersive training scenarios. Among the factors that contribute to intensifying this feeling, the SoA stands out. According to Jeunet *et al.* [2018], the SoA corresponds to the perception that "I am the one causing or generating an action," expressing the feeling of control over one's actions and their effects on the environment. These authors proposes that SoA can be understood as a two-level process: an implicit level, called sense of agency, and an explicit level, called judgment of agency. The feeling of agency is pre-reflective and non-conceptual, occurring in the early stages of action, before full integration of sensory feedback. The judgment of agency, in contrast, is reflective and conceptual, arising from the comparison between the predicted outcome and the outcome perceived after the action.

The feeling of agency emerges in the early stages of motor control, supported by internal sensorimotor signals and the intention to act. It precedes the action's outcome and does not initially depend on external sensory processing [Evangelou *et al.*, 2023].In contrast, the judgment of agency results from the conscious analysis of what was expected versus what actually occurred, relying on perceived sensory feedback. Thus, while the feeling of agency represents the immediate experience of "doing," the judgment of agency corresponds to the conscious attribution of authorship, that is, "I did this". A simple example helps to differentiate these levels: when pressing a switch, the feeling of agency manifests as the pre-reflective motor fluidity that precedes the action, when the internal prediction about resistance and the tactile "click" coincides with the movement performed, producing an automatic feeling of control. Then, the judgment of agency emerges as a conscious conclusion ("I turned on the light"), formed after the brain integrates multiple external feedbacks such as a button displacement, the sound of the mechanism, and the visual confirmation of the illumination, whose congruence with the initial intention confirms action authorship.

For an agency judgment to attribute the action to the user, three fundamental conditions must be met [Jeunet *et al.*, 2018]: Principle of Priority: conscious intention must precede action, which must precede the perceived outcome. Visual latency in VR systems, for example, violates this principle and reduces the judgment of agency; the Principle of Consistency: the observed sensory outcome must be congruent with the predicted outcome. Inversions of movement (e.g., moving one finger and seeing another move on the avatar) or spatial distortions create inconsistencies that impair the agency experience, and the Principle of Exclusivity: the user must perceive their actions as the only possible cause of the outcome. Autonomous avatar movements or unsynchronized responses violate exclusivity and diminish the attribution of authorship.

In VR, SoA comprises one of the dimensions of the Sense of Embodiment, working in conjunction with the sense of bodily ownership to validate the user's interaction with the simulated environment. Rückert *et al.* [2024] emphasize that a robust SoA, supported by synchronized motor responses and coherent multisensory feedback, strengthens the sense of spatial presence and perceived realism.

Tactile interaction plays a significant role in modulating SoA in VR. It functions as an external sensory cue that confirms motor predictions and reinforces the conscious judgment of control over actions performed in the virtual environment. Evangelou *et al.* [2023] argue that the presence of haptic feedback significantly strengthens explicit SoA, allowing users to report a greater sense of control over virtual objects compared to purely visual interactions. According to the authors, tactile feedback can also compensate for temporary losses in visual fidelity, such as latency or tracking failures, helping to preserve the coherence of the authoring experience even when the visual channel is compromised.

4 Development

This work started from the premise that tactile interaction is crucial for the effectiveness of VR simulations aimed at training in the healthcare field, while commercial haptic solutions often impose barriers related to cost, complexity, and mobility restrictions, as discussed previously. In this context, an application was designed to simulate the manipulation of a virtual surgical instrument (a scalpel) using tactile guides, that is, everyday physical objects used as haptic proxies. When manipulating a real object, the user receives tactile stimuli consistent with the action visualized in the virtual environment, without the need for specialized hardware.

The application was developed for the Meta Quest 2 Head-Mounted Display (HMD). The virtual environment and interactions were implemented in the Unity 3D game engine (version 2022.3.62f1), with technical choices geared towards the stability of the prototyping cycle and performance in standalone VR applications. To optimize interaction fluidity and visual quality, the OpenXR Toolkit was used. The compilation, installation, and testing cycle on the device was managed through the Meta Quest Developer Hub, enabling continuous debugging and validation directly on the headset. In parallel, project versioning was organized with Unity Version Control (Plastic SCM), ensuring traceability of modifications throughout the iterations, a relevant aspect in experimental scenarios where adjustments to scaling, collision, and interaction points require successive refinements. The design and implementation process adopted a modular approach to facilitate integration between components and allow iterative adjustments as needed for the study, establishing an extensible base for experiments.

4.1 Tactile Guides

An initial step in developing the proposed solution consisted of defining the tactile guides used to represent the scalpel in the virtual environment. The selection was based on the results presented by Tinguy *et al*. [2019] and in the concept of Substitutional Reality proposed by Simeone *et al*. [2015], considering that physical objects can be mapped to a virtual object as long as they maintain functional correspondence, even if they present some degree of discrepancy.

To explore this approach, four objects were selected (pencil, ruler, syringe, and real scalpel without blade) representing different levels of tactile fidelity and geometric congruence in relation to the virtual scalpel (Figure 2). Although the objects presented different levels of geometric and ergonomic congruence with the virtual scalpel, they were selected to have dimensions broadly comparable to those of the surgical instrument represented in the simulation. This choice allowed the experiment to focus on perceptual and ergonomic differences, such as shape, grip, weight, texture, and thermal sensation, while avoiding large-scale size discrepancies between the real and virtual objects. The selection of these objects was guided by their accessibility as everyday items readily available to students. This choice allowed us to investigate how physical similarity influences user immersion and comfort during interaction. The pencil was chosen for its familiar grip, while the real scalpel without blade was included for its high tactile fidelity, both serving as references for ergonomics and alignment between form and function. In contrast, the ruler was purposefully selected as a poorly ergonomic object for the surgical task, representing an extreme of cognitive-tactile dissonance. The syringe, in turn, explored an intermediate level of plausibility, with a specific grip, but distinct from that of a scalpel. For all objects, temperature was evaluated to assess how their materials (plastic and wood) could influence thermal perception compared to a real metallic scalpel.

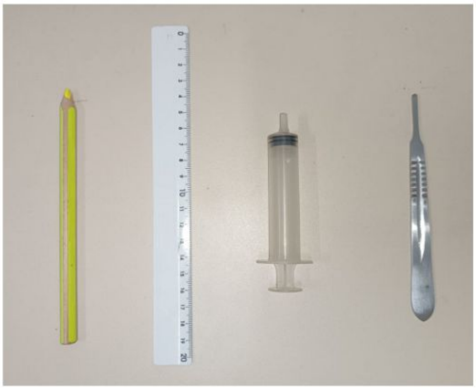

Figure 2. Objects selected as tactile guides for the experiment.

```
wait for the user's hands to be positioned on the actual table.
enable tracking
while tracking is active, do
        if both the left and right hands are available then
                calculate average hand position
                calculate average hand rotation
                position virtual table
                align table rotation to the Y-axis.
                display temporary representation of the instrument
                wait for the actual objects to be positioned in the indicated locations
                activate definitive objects
                disable temporary representation
                disable tracking
        end if
end while
```

Figure 3. Algorithm for configuring objects during application execution.

4.2 Tracking and Synchronizing Objects

Implementing the experiment in Meta Quest 2 presented challenges that required specific engineering and experimental protocol decisions, conditioned by the limitations of the available tracking system. Since the equipment does not allow for automated tracking of the physical objects used as tactile guides, the spatial correspondence between the visualized virtual objects and the manipulated physical objects was ensured through manual positioning at the beginning of the experiment. Upon starting the application, the user is placed in an empty virtual environment and instructed to position their hands on a physical table. After a predetermined time interval, counted from the start of the application, the hand position is used as a reference to begin the process of generating the other elements of the scene.

Through hand tracking, the position and rotation of the physical table are identified, allowing the creation of its virtual counterpart. In this way, the physical table acts as a tactile guide for the virtual table. From the positioning of the virtual table, virtual objects are generated. Initially, these objects are presented as temporary representations, used to assist the user in positioning the physical objects that will act as corresponding tactile guides. After this stage, the definitive virtual objects are generated in the established positions.

This technical limitation may affect the natural flow of interaction, but it was incorporated in a controlled manner into the experimental protocol, preserving the validity of the feasibility test of the approach. This strategy allowed the evaluation to focus on the user's perceived experience and tactile properties such as weight, shape, thermal sensation, texture, and grip. Given the limitations imposed by the hardware used, a specific algorithm was developed to prepare the virtual environment and enable synchronization between the physical and virtual spaces (Figure 3).

The algorithm uses the arithmetic mean of the position and rotation data of the user's left and right hands to determine the appropriate height and orientation for generating virtual objects. After this identification, the system visually displays the selected position for each object, allowing the user to position and adjust the physical objects before the final generation of their virtual counterparts. This procedure

Figure 4. Visualization of the experimental environment with the 4 scalpels and the location where the incision will be made.

reduces misalignments and potential discrepancies between the tactile guides and the virtual objects.

During the manipulation of physical objects in the VR environment, it was observed that the presence of the object in the user's hand, partially occluded, interfered with the hand tracking provided by the device. This interference triggered the function responsible for ending the interaction between the virtual object and the virtual representation of the hands. The behavior occurred because the tracking system, failing to identify the physical object, interpreted it as part of the hand and therefore that the hand was not holding the object. To avoid this problem, the execution of the virtual object release was restricted to a specific hand pose. This pose was configured as the fully open hand position with fingers spaced apart, preventing undue interruption of the interaction during the manipulation of the tactile guides.

4.3 Interaction Scenario

The virtual scenario was developed as a straightforward procedure room, where the user is seated at a table and observes the environment from a first-person perspective. To begin the simulation, the participant places their hands on the physical table and waits for the virtual elements to appear. On the virtual table are presented four visually identical virtual scalpels (Figure 4) identified by the letters A, B, C, and D, whose real counterparts are the objects shown in figure2: pencil, ruler, syringe, and scalpel, in that order. Below these instruments there is a "surgical zone", represented by an orange circle, which delimits the area where the incision task should be performed.

The core of the interaction is based on the direct correspondence between each virtual scalpel and a distinct physical tactile guide. Thus, when selecting and manipulating an instrument in the virtual environment, the user simultaneously holds the corresponding physical object. The task consists of picking up each of the virtual scalpels and making a cut in the orange circle, repeating the procedure successively with each tactile guide. During execution, the system reproduces, in the virtual environment, the movements of the participant's hands, contributing to a consistent perception of motor control and agency throughout the activity.

The interaction for selecting and manipulating virtual scalpels utilizes hand tracking provided by the Meta Quest 2 HMD. When the user picks up a virtual scalpel using the controller, they simultaneously manipulate the associated physical object. In this way, the system integrates the visual feedback provided by VR with the tactile feedback from the real object, establishing a sensorimotor correspondence between physical action and virtual response.

This interaction scenario was structured to serve as the basis for conducting the experiment described below, detailing the procedures adopted, the tasks performed by the participants, and the criteria used for data collection and analysis.

4.4 Experiment

Following the development of the application, an experiment was designed to investigate how the different properties of physical objects influence the user experience in a virtual reality environment aimed at surgical training. To this end, a questionnaire was developed in 3 sections to address: 1) participant profile, 2) assessment of perceived discomfort in relation to the different characteristics of each of the virtual scalpels, 3) motivation and assessment of the participant's overall experience with the simulation and with each scalpel.

In section 2 of the questionnaire, the participant answers questions related to discomfort regarding the weight, shape, thermal sensation, texture, and grip of the scalpels. In this context, a low correspondence between intention and sensory feedback leads to increased discomfort, associated with a reduction in the SoA [Greensdale *et al.*, 2023]. The questions are of the type: "Considering *P* of each item, did you experience any discomfort while using any of the scalpels? Check all that apply". *P* refers to the property (weight, shape, thermal feel, texture or handle) and the options have the letters of each of the scalpels (A, B, C and D).

In section 3, the participant responds to statements using a Likert scale from 1 to 6, where 1 represents "Strongly Disagree" and 6 represents "Strongly Agree". The statements are as follows:

- "I would like to conduct training in a virtual reality environment that uses this type of approach for the manipulation of surgical instruments."
- "I would feel motivated to conduct training in a virtual reality environment that used this type of approach to the manipulation of surgical instruments."

In the last two questions of this section, the participant rates the experience between "Very Uncomfortable" and "Very Comfortable" on a Likert scale of (1-6) and can freely provide (textual) observations about their experience.

The experiment consisted of two phases: the first aimed to validate the questionnaire and the application testing protocol, and the second aimed to evaluate the application with the target audience. The experiment was approved by the Research Ethics Committee of the Health Sciences Center (CEP-CCS) of the Federal University of Paraíba, under opinion number 82243724.7.0000.5188, and included 24 participants: 11 in the first phase and 13 in the second. Participation was voluntary and anonymous, with a guarantee of confidentiality of information, intended exclusively for academic purposes.

The testing protocol was structured as follows: prior to the participant entering the room, the researchers prepared the environment, including manual tracking and spatial alignment between the physical objects and their virtual counterparts, ensuring that both were positioned coincidently at the start

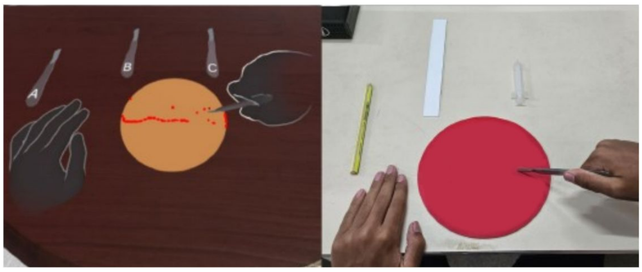

Figure 5. Virtual world (left), as viewed by the participants, and real world (right) of the experiment.

of the session. Once this step was completed, the physical objects were covered, and the participant was invited to enter the environment, sit at the table, and put on the HMD. In this way, the participant was unaware of which objects were on the real table. Only after the participant donned the device were the objects uncovered, initiating the interaction, during which only the virtual scalpels could be seen. At the end of the session, the objects were covered again before the participant removed the HMD.

The questionnaire and testing protocol were validated in the first phase with participants over 18 years of age, university students or professionals with higher education degrees from different fields of knowledge [Costa *et al.*, 2025]. In the second phase, which involved using the application and completing the questionnaire, participation was limited to university students or healthcare professionals who had completed a course in surgical techniques. These participants used the virtual environment for approximately 20 minutes. During the task, they could select and manipulate each scalpel, simultaneously holding the corresponding virtual and physical object (tactile guide) and perform the cutting movement in the surgical area defined by the application (Figure 5). This procedure was repeated for each of the four scalpels. Participants were free to use both hands during manipulation. After completing the interaction, they filled out the questionnaire.

It is important to note that the validation and test groups differ substantially in their composition and level of expertise, particularly due to the inclusion of health sciences professionals in the validation group. Therefore, the comparison of results from both groups was not considered in this study, as these differences could introduce bias and lead to misleading interpretations.

5 Results

The application evaluation involved 13 participants, 2 from the Nursing field and 11 from Medicine, all with knowledge of surgical techniques. Among them, eight participants had never used a virtual reality environment.

When asked about discomfort regarding the weight of scalpels A (pencil), B (ruler), C (syringe), and D (bladeless scalpel), only scalpels B and C were reported as uncomfortable by the participants (3 and 1 responses, respectively), with no reports regarding the other objects. Scalpel B was also the object most frequently reported as uncomfortable, with 38.46% (five) of participant responses. Texture was reported as uncomfortable in scalpels A (2 reports), B (2 reports), and C (1 report). Thermal sensation was reported as uncomfortable only once in scalpels A and D. Overall, the format had the greatest impact on participant discomfort (Figure 6).

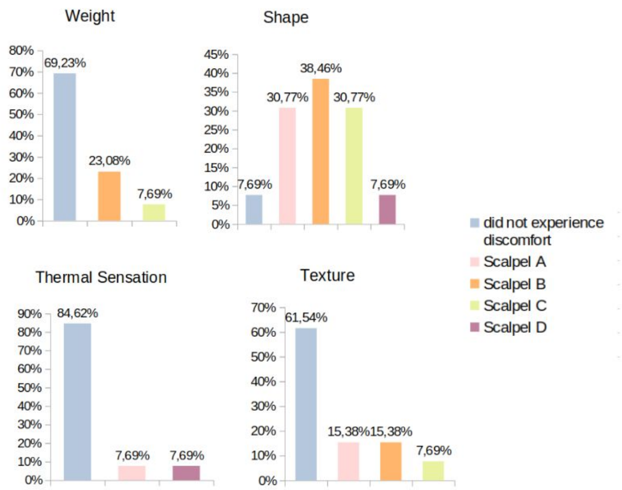

Figure 6. Discomfort reported by participants related to perceived weight, shape, thermal sensation and texture.

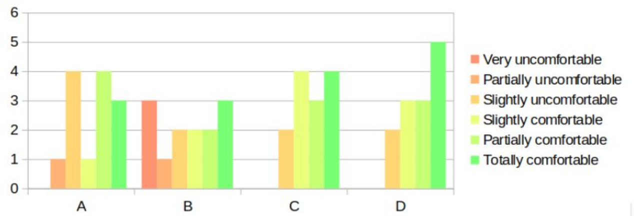

Figure 7. Evaluation of the overall experience with each virtual scalpel.

The greatest divergences in responses were reported regarding the handling of the objects, with discomfort occurring for all of them. In this item, participants considered three factors: (1) the way the objects were grasped, (2) the tactile sensation of the object in the cutting area, and (3) the visualization of the cut. Reports concerning the way the object was picked up from the table (1) and its adaptation to the hands occurred because participants had experience with surgical instruments and manipulated the virtual scalpel as they would a real scalpel, which was not accurately recognized by the system. Since virtual–real synchronization was performed at the beginning of each session, divergences in the position of the tip of the real and virtual scalpel during the interaction caused the real object to touch the surface before the virtual object, or the virtual object to touch the surface without the real object doing so (2). As a result, participants either saw the cut but did not feel it, or felt the cut without seeing it (3). These difficulties were reported in the observations recorded in the open-ended section of the questionnaire.

Regarding the desire to perform training using the adopted approach, considering each object, 61% of participants agreed with the use of Object A (ratings 4, 5, and 6 on the scale), 53% with Object B, 85% with Object C, and 92% with Object D. Motivation agreement percentages were 46%, 46%, 85%, and 85% for Objects A, B, C, and D, respectively.

In the evaluation of the overall experience with each scalpel, only the experience with Object B (ruler) was rated as “very uncomfortable.” Nevertheless, participants considered the overall experience with all objects comfortable when combining the Comfortable categories (Slightly, Partially, and Totally), as the combined percentage of these three categories exceeded 50% in all cases (Figure 7).

6 Discussion

Although previous studies have explored the use of everyday objects to enhance immersion and the naturalness of interaction, these studies focused on generic tasks and a diverse audience, without specifically addressing experiences or objects in the context of medical simulations. Accordingly, the present study evaluated the manipulation of physical and virtual scalpels in a surgical simulation context, focusing on the experience of handling physical objects and their virtual counterparts. Geometric, ergonomic, and perceptual parameters were analyzed in an integrated manner, including weight, shape, texture, thermal sensation, and grasp, as well as the consistency between physical sensation and visual feedback during the cutting action.

Previous studies in augmented reality and tangible interfaces report consistent results regarding the importance of physical form. Kahl and Krüger [2023] demonstrated that abstract physical objects (proxies) can support effective interactions in AR as long as they maintain basic structural similarity with virtual objects, highlighting that excessive shape discrepancies compromise the manipulation experience. Similarly, Kwon *et al*. [2009] found that differences in shape and size between physical and virtual objects significantly affect usability, with shape being more critical than size for perceived realism and performance in manipulation tasks. In the present study, inappropriate shape also directly caused discomfort, demonstrating that in tasks requiring precision, physical correspondence is not limited to visual perception but also involves ergonomic comfort and grasp adaptation. This aspect complements the findings of Kobeisse and Holmquist [2022], who showed that physical replicas coherent with virtual objects increase naturalness and immersion, while the present study extends this analysis by considering weight, texture, thermal sensation, and physical–virtual synchronization—factors that have been little explored in studies on abstract physical proxies.

The limits of perception of physical objects observed by Bergström *et al*. [2019] and Kobeisse and Holmquist [2022] indicate that users can tolerate small scale discrepancies without perceiving significant differences. In the present study, even moderate differences between the physical form and the expected virtual action were sufficient to generate discomfort, suggesting that in specialized tasks, perceptual correspondence alone does not guarantee ergonomic comfort or manipulative effectiveness. The results of Bergström *et al*. [2019] on perceptual tolerance to tactile variations emphasize psychophysical perception limits, but this perspective does not incorporate ergonomic or kinesthetic aspects—such as grasp or thermal sensation—which were addressed in the present study as essential in health simulations. This study, however, shows that the experience of discomfort is associated not only with perceived discrepancy but also with complex kinesthetic interaction, particularly in tasks requiring fine manipulation, such as surgical procedure simulation. This finding contrasts with Tinguy *et al*. [2019], who showed that moderate tactile variations may not be perceived by the user as long as overall feedback is coherent.

7 Conclusion

Unlike previous studies, the present study differs by being conducted in a specific surgical simulation application, involving specialized participants with prior knowledge in the field, which increases the practical relevance of the results for medical contexts. Nevertheless, as a limitation, it should be noted that the sample size of the present study was small (n = 13), restricting the generalizability of the results and indicating the need for future investigations with a larger number of participants to validate and further explore the observed trends. In this regard, it is worth noting that previous studies also used small samples: Tinguy *et al*. [2019] included 17 participants; Kobeisse and Holmquist [2022], 16; Bergström *et al*. [2019], 14; and Rückert *et al*. [2024], 35 participants. Moreover, these studies conducted experiments of a generic nature, without a specific target audience.

In contrast to previous studies, the present study provides a broader analysis than just form–virtual correspondence, integrating body perception, ergonomic comfort, and synchronization between physical sensation and visual feedback. These factors are particularly relevant in the context of health simulation, where physical manipulation needs to be intuitive, natural, and comfortable to replicate real procedures. In this regard, the use of tactile guides and coherent physical proxies could constitute an alternative approach to haptic devices, providing sufficient physical feedback for realistic training experiences without the need for complex haptic equipment.

In the context of surgical simulation, where haptic interaction is essential for developing manual dexterity, the results of the present study suggest that discrepancies between physical sensation and visual feedback can negatively impact the sense of control over actions (Sense of Agency) [Rückert *et al*., 2024]. The use of coherent physical proxies, combined with realistic haptic feedback or tactile guides, has the potential to enhance perceived presence and strengthen SoA, promoting a more natural, reliable, and engaging training experience, particularly in tasks requiring manual precision.

This study focused on isolating the effect of the instrument by keeping other factors, such as the material properties of the table and the interaction region, constant across all conditions. While this controlled design ensured comparability, we acknowledge that material properties may influence haptic perception in more realistic scenarios. As future work, we intend to investigate these factors in the context of applying the proposed technique to realistic training simulations. In addition, future studies will explore broader discrepancies between the dimensions of real and virtual objects, including cases in which the physical proxy is substantially smaller or larger than its virtual counterpart, in order to better understand the tolerance limits of real–virtual size correspondence in surgical simulation tasks.

Declarations

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Authors' Contributions

Authors Contributions: LSM: Conceptualization, Methodology, Software, Experimentation, Formal analysis, Writing – Original Draft, Writing – Review & Editing. ACVA: Software, Experimentation, Writing – Original Draft. DSC: Software, Experimentation, Writing – Original Draft. EEV: Writing – Original Draft, Writing – Review & Editing. JGF: Experimentation, Formal analysis, Writing – Original Draft. MLHM: Experimentation, Writing – Original Draft. RMM: Formal analysis, Writing – Original Draft, Writing – Review & Editing.

Competing interests

"The authors declare that they have no competing interests".

Availability of data and materials

Supplementary material is available on the paper's publication page (`https://doi.org/10.5753/jis.2026.7623`) and includes the questionnaire and the database with responses of the two phases of the Experiment: validation of the protocol and tests with target public.

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