Study of Haptic Feedback Impact on Learning Basic Surgical Technical Gestures

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ABSTRACT

The increasing integration of Virtual Reality (VR) in surgical training has prompted significant investigation into its efficacy for skill development and transfer. While the majority of existing research has focused on the graphical aspects of these simulators, the role of haptic feedback remains less explored yet potentially pivotal. Our study aims to investigate the impact of haptic feedback on surgical skill acquisition, transfer, and retention within a VR-based training environment. We developed a VR simulator for a bi-manual "Ring Transfer" task, with and without haptic feedback, and designed a corresponding physical simulator to measure skill transfer to real-world tasks. We recruited 24 volunteers, divided into three group: force feedback (FC), no-haptic feedback (NC), and control (CC), to undergo training and evaluation. Our hypotheses posit that haptic feedback will not only improve task performance and sense of presence within the VR environment but also facilitate more effective skill transfer and retention in real-world settings. This research aspires to bridge existing gaps in our understanding of the value of haptic feedback in VR-based surgical training, offering insights for curriculum design and simulator development.

Keywords: Virtual Reality, Surgical training, Haptic feedback.

1 INTRODUCTION

With the growth of technological advancements and evolving surgical techniques, virtual reality (VR) simulators have become a fundamental element in the training curriculum for both novice and experienced surgeons [1]. Over the past two decades, these systems have provided a safe and controlled setting for repetitive skill practice, thereby eliminating the risks associated with real-world surgical errors on humans and animals. Concurrently, there has been a research focus on enhancing the fidelity and performance metrics of these simulators, aiming for effective knowledge and skill transfer from the virtual environment to actual operating rooms [2].

However, the majority of efforts in surgical simulation have prioritized graphical fidelity over tactile and force feedback, commonly known as haptic feedback [3]. While graphically-intensive systems may have advantages such as lower computational requirements and cost-effectiveness, empirical studies highlight the significant impact of haptic feedback on consistent and accelerated skill acquisition among trainees.

The concept of automaticity is crucial in surgical skill development, defined as the ability to perform tasks quickly and accurately while managing other cognitive functions [4]. Achieving this level of automaticity allows surgeons to allocate cognitive resources to different aspects of the surgical procedure. Thus, the incorporation of appropriate haptic feedback is essential for trainees to focus effectively on specific clinical tasks, particularly those requiring precise instrument control and tissue manipulation [5].

It's crucial to acknowledge the intricate and nuanced perspectives offered by existing research on the role of haptic feedback in surgical training simulators. Some studies provide compelling evidence for the benefits of incorporating haptic feedback, especially when used in combination with other sensory enhancements like 3D visualization and stereoscopic vision [6, 7, 8, 9]. However, counterarguments arise from research [10, 11, 12] that questions the overall efficacy of haptic feedback, positing that visual cues alone may suffice or even exceed haptic feedback in certain scenarios. Importantly, the effectiveness of haptic feedback appears to be influenced by a range of variables, such as the complexity of the task, the specific requirements of the surgical procedure, and the level of expertise of the participant. These factors introduce additional complexities to our understanding and necessitate a cautious interpretation of existing data.

Expanding upon the existing knowledge of haptic feedback's role in VR surgical simulators, it is imperative to delve deeper into the conditions under which haptic feedback proves most beneficial. The effectiveness of these systems hinges on training transfer, typically measured by how well a trainee can apply the skills and knowledge acquired in a virtual setting to real-world tasks. In this context, simulator fidelity— the degree of resemblance between what is taught in a simulator and what is required in a real-world environment [13, 14]—becomes a key metric for evaluating the efficacy of training simulations. To assess this, it is essential to examine a trainee's performance in actual surgical tasks following proficiency in a simulated environment.

Zhou et al.'s study [15] indicated that early integration of haptic feedback in laparoscopic training leads to faster and more consistent learning, but questioned its long-term necessity and the unexplored aspect of real-world skill transfer. In contrast, Chmarra et al. [16] emphasized the positive impact of force feedback on skill acquisition and noted successful skill transfer when training initially used a more realistic box trainer, an effect not seen with VR-based training. However, Våpenstad et al. [17] found that haptic skills gained in VR did not effectively transfer to clinical settings, with the control group outperforming the simulator-trained group on multiple metrics. This disparity was attributed to the inadequacy of the simulator's haptic feedback, underscoring the need for further research on the efficacy and limitations of simulated haptic feedback in surgical training.

Despite the growing recognition of haptic feedback as an integral component in effective surgical training, there is still uncertainty regarding the optimal characteristics required to design a comprehensive training curriculum that can enhance learning and skill transfer across specific medical tasks [18]. To address this research gap, our study aims to examine the effect of haptic feedback on sense of presence, task performance during training via a VR immersive simulator, and the subsequent transfer and retention of these acquired skills in a real-world context. Through the outcomes of this study, we aim to offer guidance on how to effectively integrate haptic feedback in immersive VR systems tailored for surgical skill training.

2 METHODOLOGY

Our research intends to study the impact of haptic feedback on the acquisition of basic surgical skills in immersive VR platforms. The main objectives include examining the learning trajectory, as well as the transfer and retention of these acquired skills in real-world situations. Additionally, we aim to investigate whether haptic feedback could enhance the user's sense of presence and overall usability within the VR training context. We proposed the following hypotheses:

(H1): The integration of haptic feedback during virtual reality learning improves the fidelity of interaction and the sense of the presence of learners, leading to a more immersive user experience and more effective transfer of skills acquired in real life.

(H2): Both training groups (haptic and no-haptic) will outperform the control group in real-world task efficiency and accuracy after VR training, showcasing effective skill transfer and retention.

(H3): Participants who receive virtual reality training with haptic feedback will have better performance in performing technical gestures in both VR and real life compared to learners who have been trained without haptic feedback.

In order to validate these hypotheses, we developed a VR simulator to facilitate training in a bi-manual "Ring Transfer" task, with and without haptic feedback. To assess the transfer of these skills to real-world scenarios, we also designed a closely matched physical simulator.

2.1 Participants

A sample of twenty-four volunteers (14 males and 10 females) were recruited to participate in the study (n = 24). The sample was randomly divided into three groups: a force feedback group (FC), a no-haptic feedback group (NC), and a control group (CC). The experimental protocol was validated by the Research Ethics Committee of the Université Paris Saclay. The study complied with the requisite ethical standards, and all participants provided informed written consent before participating.

2.2 Apparatus

The experimental setup included several key components and materials. These consisted of two Geomagic Touch haptic devices and an Oculus Quest 2 virtual reality headset (Figure 2). Additionally, a desktop computer (Intel(R) Xeon(R) Silver 4214R CPU, an NVIDIA GeForce RTX 3080 GPU, and 32 GB of RAM) was utilized for the experimental tasks. For the physical aspect of the study, a prototype system was employed, featuring two electromagnetic tools designed for object manipulation, a set of metal washers, and a wooden support structure with pegs for placing the washers (Figure 1). Moreover, for groups 1 and 2, a 3D virtual environment was provided that matched the physical prototype. This virtual setting included a virtual table, a support platform with pegs, two virtual tools controlled by the haptic arms, and virtual washers that participants manipulated. It is important to note that participants in Group FC were able to perceive the forces generated from collisions between the virtual objects being manipulated (washers, tools, and pegs).

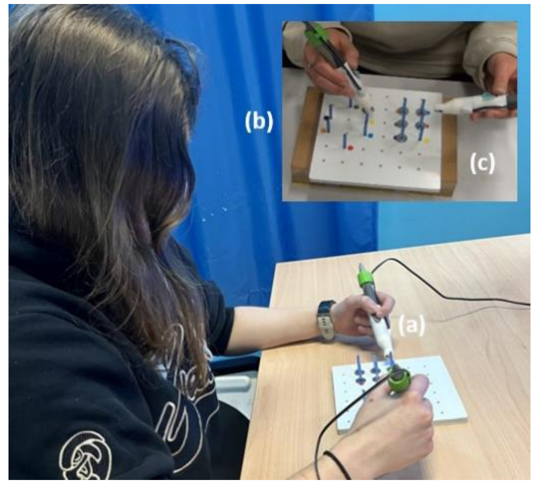

Figure 1: Physical prototype (a: electromagnetic tool, b: physical setup, c: wooden support with 12 pegs and metal washers)

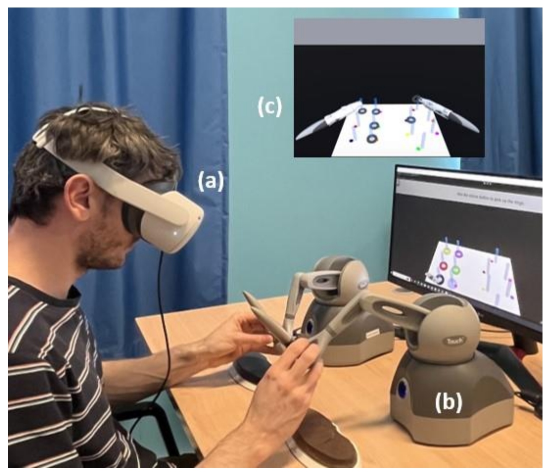

Figure 2: Virtual prototype (a: VR headset, b: haptic interfaces, c: virtual environment)

2.3 Experimental Task

In the real-world task, participants were required to perform a simple manipulation inspired by the "Ring Transfer" task using electromagnetic tools. They had to move six metal washers and place them onto pegs following a specific color pattern. To complete the task, participants were initially instructed to grasp a washer with the tool controlled by their left hand, transfer it to the tool controlled by their right hand, and place it on a peg on the left side. Once all the washers were placed on the left side, participants were then instructed to transfer them back to the left tool using the right tool and place them back onto the pegs. The electromagnet on each tool was activated by pressing a button. This task was repeated three times by the three experimental groups, and the experimenter recorded performance measures such as time and accuracy on a digital document. The VR experimental task involved performing the same task but using two haptic devices in the virtual environment. The participant moved the six 3D washers using two virtual tools. The position and orientation of the tools are determined by the haptic devices used. In the first experimental condition (group 1), the user was able to feel forces (in 3 degrees of freedom) on each of these devices, allowing them to perceive collisions between the tool, manipulated objects, and pegs. In the other condition (group 2), haptic feedback was disabled. Performance measures (time and accuracy) were automatically recorded by the application in a text file.

2.4 Experimental Procedure

All groups performed the peg transfer task in a real-life setting to establish a baseline measure of their current skills. After this session, the force feedback group and the no-haptic feedback group received a VR familiarization session to acclimate to the virtual reality environment and learn how to interact with the haptic devices. Following this, the training sessions began. The force feedback and no haptic feedback groups completed the peg transfer task in the VR environment with their respective forms of haptic feedback. The control group received no training. At the end of the training sessions, all groups performed the peg transfer task again in the real-life setup. This will allow for a comparison of performance before and after training and provide a measure of the transfer of skills from the virtual environment to the real-life task. The objective is to study the learning curve of the participants during four experimental phases: a pre-test, a training phase, a post-test, and a retention test (Figure 3). The results of this study will be used to explore the effectiveness of integrating haptic feedback on the learning transfer and retention of skills from VR simulators to the real-world.

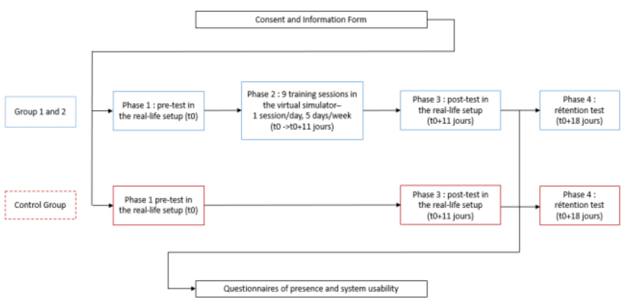

Figure 3: Summary of the Experimental Procedure.

2.5 Data collection and analyses

Following the completion of the training sessions, the analysis of data in this study includes several performance measures to assess the participants' progress. These measures consist of the task completion time and the number of errors, which are counted as objects dropped during the trials. These quantitative measures provide objective indicators of participants' skill acquisition and performance improvements. Additionally, subjective measures are incorporated to gather participants' feedback and perceptions. At the end of the experiment, participants are asked to complete the System Usability Questionnaire (SUS), a standardized questionnaire widely used to evaluate the usability of systems. This questionnaire helps assess participants' subjective evaluation of the VR simulator and its ease of use. Moreover, participants' sense of presence in the virtual simulator is assessed using a comparative questionnaire based on the established method proposed by Witmer and Singer (1998) for measuring presence in virtual environments. This questionnaire offers a qualitative evaluation of participants' level of immersion and their subjective perception of realism within the virtual environment.

3 Conclusion

The role of haptic feedback in surgical training is a subject of increasing importance but remains relatively underexplored, particularly in the context of virtual reality (VR) simulators. Existing studies have illuminated various facets of haptic feedback's potential advantages and limitations. However, there is a pressing need for methodologically rigorous research that evaluates its impact on skill acquisition, transfer, and retention in real-world surgical settings. To address this research gap, our study introduces a comprehensive framework, featuring a VR simulator specifically designed for the "Ring Transfer" task. This task is a cornerstone in laparoscopic training and serves as a fundamental proxy for complex surgical maneuvers. We have also constructed a closely matched physical prototype to serve as a benchmark for real-world skill transfer.

Our study design is characterized by its focus on both subjective and objective evaluation metrics. Objective measures such as task completion time and error rates offer quantitative assessment of skill acquisition, while subjective measures like System Usability Questionnaires and presence assessments provide insights into the user experience. This multi-faceted approach aims to contribute to a deeper, more nuanced understanding of haptic feedback's role, not just as a technological add-on but as an integral component that could potentially redefine VR-based surgical training.

To reinforce the generalizability of our findings, the study employed a randomized controlled design, enrolling participants into force feedback (FC), no-haptic feedback (NC), and control groups (CC). Moreover, the use of a physical simulator as a baseline for real-world skill transfer is another key strength of our methodology. Not only does this allow for a direct measure of training transferability but it also provides a more comprehensive perspective of how haptic feedback could influence performance in an actual surgical environment.

In terms of immediate and long-term implications, our study's design promises invaluable insights for curriculum design and simulator development. If our hypotheses are validated, surgical training programs could opt for a more integral incorporation of haptic feedback into their VR training modules. This could even lead to task-specific or expertise-level tailoring of haptic feedback. Conversely, if haptic feedback proves less influential under certain conditions, this knowledge would serve to guide selective implementation strategies, optimizing both resources and learning outcomes.

While the present paper is confined to detailing our research methodology and study design, it paves the way for the ensuing phases of data collection and analysis. These future works aim to validate our hypotheses and provide a more granulated understanding of haptic feedback's influence on surgical skill acquisition and transfer in VR environments.

In summary, the methodological framework of this study, inclusive of our custom-designed VR simulator for the ring transfer task and its closely matched physical prototype, aims to illuminate the intricate relationship between haptic feedback and surgical skill development in virtual learning environments. With its rigorous methodology and multi-dimensional evaluation schema, our research hopes to make a contribution to the body of literature on surgical simulators, thereby shaping the future contours of surgical training curricula.

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