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Enhancing Operator Skill Transfer: The Role of Real-Time Haptic Feedback in VR Engineering Simulations

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ABSTRACT

The acquisition of complex, high-precision psychomotor skills for industrial operations remains a significant challenge, often relying on costly and risky on-the-job training. While Virtual Reality (VR) simulations offer a safe and scalable alternative, their predominant focus on visual and auditory cues fails to replicate the critical haptic feedback essential for developing true proficiency. This study investigates the efficacy of integrating real-time haptic feedback into a VR engineering simulation for operator skill transfer. A between-subjects experimental design was employed, with novice participants randomly assigned to either a haptic-enabled training group (using Sense Glove Nova) or a visual-only control group. Following multiple training sessions, performance was assessed on a real-world pneumatic valve assembly task immediately after training and again after a one-week retention period. Quantitative results demonstrated that the haptic group completed the task significantly faster and with far fewer errors, particularly force-related mistakes like cross-threading. This performance advantage was maintained at the retention test, indicating deeper learning consolidation. Subjective data revealed the haptic system was perceived as more usable and realistic, while also reducing mental frustration. Qualitative analysis highlighted that haptic feedback provided critical confidence-building tactile cues. The findings strongly support the hypothesis that haptic feedback, by fostering embodied learning through enriched sensorimotor loops, is a critical determinant for effective skill transfer. This research concludes that high-fidelity haptics are not an optional enhancement but a necessary component for VR training systems aiming to achieve genuine operational proficiency in engineering domains.

Keywords: Virtual Reality, Haptic Feedback, Skill Transfer, Operator Training,

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Embodied Cognition, Engineering Simulation, Industrial Training

Introduction

The modern industrial landscape is characterized by an increasing complexity of engineering systems and a pressing skills gap, creating a critical demand for highly effective training methodologies. Traditional training for high-precision tasks such as the assembly of precision actuators, the maintenance of hydraulic systems, or the machining of composite materials often relies on costly, time-consuming, and potentially hazardous on-the-job training using physical prototypes and machinery (Liang et al., 2022). This approach not only risks damage to expensive equipment and materials but also presents significant safety concerns for novice operators. Furthermore, the subjective nature of expert-led instruction can lead to inconsistencies in skill transfer, making it difficult to standardize proficiency across a workforce. The challenge, therefore, lies in developing a training paradigm that can faithfully replicate the psychomotor and cognitive demands of real-world tasks in a controlled, safe, and scalable environment without sacrificing the depth of learning required for operational mastery.

In response to these challenges, Virtual Reality (VR) has emerged as a transformative tool for industrial training simulations. By immersing trainees in interactive, computer-generated environments, VR provides a safe space to practice complex procedures, make mistakes without real-world consequences, and repeat tasks until proficiency is achieved (Smith & Ericson, 2021). The strengths of conventional VR training are predominantly visual and spatial; trainees can learn the sequence of operations, navigate large-scale virtual machinery, and develop a strong spatial understanding of components and their relationships. This visual immersion has been proven to enhance engagement and improve the retention of procedural knowledge compared to traditional methods like manuals or videos. The scalability of VR also allows for the simultaneous training of a distributed workforce, ensuring that every operator receives the same high-quality, standardized instructional experience, thereby addressing a key limitation of apprentice-style learning.

However, a significant limitation persists in these visually immersive systems: the fundamental lack of tactile interaction. For many engineering tasks, visual guidance alone is insufficient for developing the nuanced fine motor skills required

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for competence. As noted by Carella and Park (2023), tasks requiring the perception of force feedback such as feeling the correct torque when tightening a bolt, discerning the texture of a surface for quality inspection, or sensing the compliance of a rubber seal during assembly are poorly served by traditional VR controllers that merely vibrate. This absence of realistic haptic information creates a cognitive dissonance where the virtual world looks real but feels hollow, preventing the development of the crucial sensorimotor loops that underpin true skill acquisition. Consequently, while trainees may excel within the VR simulation, the transfer of these skills to the physical world, where tactile cues are paramount, can be markedly limited, undermining the overall efficacy of the training investment.

To bridge this fidelity gap, the integration of real-time haptic feedback is paramount. Haptic technology, which encompasses both kinesthetic (force feedback) and tactile (vibratory, texture) sensations, provides the missing sensory channel by simulating the physical properties of virtual objects (Choi & Lee, 2024). Real-time haptic feedback refers to the immediate and computationally synchronized generation of touch-based stimuli in response to a user's interactions within the simulation. For instance, a haptic glove can render the resistance of a spring, the slip of a belt, or the sharp edge of a component, thereby providing critical cues that guide motor control and decision-making. By delivering this realistic touch sensation, haptic-enabled VR transforms the training experience from a passive visual exercise into an active, embodied learning process. This multisensory immersion is posited to significantly enhance the development of muscle memory, improve performance accuracy, and most critically, foster a more robust and effective transfer of complex operational skills from the virtual simulation to the physical workstation.

Literature Review

The theoretical underpinnings of skill acquisition provide a critical lens through which to evaluate the efficacy of any training intervention, including VR simulations. Fitts and Posner's (1967) classic three-stage model progressing from the cognitive (understanding the task) to the associative (refining performance) to the autonomous (executing without conscious effort) stage offers a framework for how complex psychomotor skills are developed. VR environments are particularly adept at supporting the cognitive stage by providing clear, visual instructions and allowing

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for error without consequence. However, progressing to the associative and autonomous stages requires consistent, reinforcing feedback to build accurate mental models and muscle memory, an area where traditional VR can falter. This is further complicated by Cognitive Load Theory (Sweller, 1988), which posits that working memory is limited. An ineffective interface or a lack of intuitive sensory feedback can impose extraneous cognitive load, hindering the acquisition of schema. The ultimate goal is positive skill transfer, where learning in a simulated environment improves performance in the real world. According to the theory of identical elements (Thorndike & Woodworth, 1901), the degree of transfer is a function of the similarity between the training and real-task conditions. Therefore, for high-fidelity skill transfer in engineering, the simulation must replicate not just the visual and procedural elements but also the critical physical and haptic interactions to ensure the cognitive and sensorimotor schemas developed are directly applicable (Wright & Kim, 2023).

The application of Virtual Reality for training has demonstrated significant promise across a diverse range of high-stakes domains, establishing a strong precedent for its use. In aviation, full-flight simulators with motion platforms have been the standard for decades, and VR now offers a more accessible and scalable alternative for procedural and emergency response training, showing high rates of skill transfer (Bennett & Stuart, 2022). In medicine, VR simulations for laparoscopic surgery have proven effective in reducing error rates and improving instrument handling skills among surgical residents, with several studies confirming transfer to the operating room (Miller et al., 2021). Within manufacturing specifically, research by O'Connor and colleagues (2023) demonstrated that VR-based training for assembly line workers led to a 30% reduction in training time and a 15% decrease in errors during the initial phases of real-task performance compared to traditional video-based training. The consistent benefits identified across these domains include enhanced spatial understanding, safe error boundaries, and the ability to simulate rare or dangerous scenarios. However, a recurring limitation noted in these studies is the challenge of training tactile-dominant skills, such as feeling the correct engagement of a component or applying the appropriate amount of force, which are often cited as the last and most difficult skills to master outside the real environment.

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Haptic technology, the science of applying touch (tactile) and force (kinesthetic) feedback to human-computer interaction, provides the tools to address this sensory gap. The hardware landscape is diverse, ranging from high-fidelity, grounded exoskeletons like the HaptX Gloves, which provide realistic force feedback and complex tactile sensations such as texture and shape, to more accessible wearable vibrotactile gloves like the Meta Quest Touch Pro controllers, which use localized vibrations to simulate contact (Abdullahi et al., 2024). Desktop devices such as the Geomagic Touch (formerly Phantom Omni) offer a cost-effective solution for applications requiring precise, point-based force feedback, such as simulating a tool tip. The software counterpart, haptic rendering, involves the algorithms that generate these sensations based on virtual object properties like stiffness, damping, friction, and texture. Force feedback rendering creates resistance against a user's motion, simulating the weight and solidity of objects, while tactile feedback focuses on simulating surface properties through vibrations and skin deformation. The technological challenge lies in creating devices that are both high-fidelity and practical for extended training use, as there is often a trade-off between the realism provided by powerful, grounded hardware and the freedom offered by untethered, wearable solutions (Garcia & Chen, 2023).

The integration of these haptic technologies into VR training simulators has been explored with encouraging results in several fields. In surgical training, systems like the SimQuest laparoscopy simulator incorporate force feedback to train suturing and cutting, with studies showing that haptic cues significantly improve the development of tissue handling skills (Van der Berg et al., 2022). In rehabilitation, haptic VR is used to guide stroke patients through movement therapies, providing both assistive and resistive forces to retrain neural pathways (Klamroth-Marganska, 2021). Research in virtual assembly has shown that the addition of force feedback can reduce task completion times and decrease the number of unwanted collisions between virtual parts (Peterson et al., 2023). However, a synthesis of this literature reveals a specific gap. While these studies prove the value of haptics for specific, often isolated, motor tasks, the research is less conclusive regarding its impact on the long-term retention and holistic transfer of the complex, multi-step procedural skills required by industrial engineering operators. These tasks often combine

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cognitive decision-making with nuanced psychomotor execution under time constraints. Therefore, while the promise is evident, there remains a pressing need for rigorous, empirical evidence focused explicitly on how the sustained use of integrated haptic-VR systems affects not just immediate performance within the simulation, but the long-term retention and robust transfer of integrated cognitive-psychomotor skills to complex real-world engineering contexts (Zhao & Lafon, 2024).

Problem Statement

The proliferation of complex, high-precision engineering tasks in industry exacerbates the challenge of training operators effectively and safely. While virtual reality (VR) simulations have emerged as a transformative tool for procedural and spatial learning, they possess a critical limitation: the absence of realistic tactile interaction. Conventional visual-and-auditory VR fails to convey essential haptic information, such as force, texture, weight, and compliance, which are fundamental for developing fine motor skills and true operational proficiency. This sensory gap prevents the formation of accurate sensorimotor schemas, thereby limiting the fidelity of the training experience and ultimately hindering the robust transfer of skills from the virtual environment to the physical workstation. Consequently, there is a pressing need to address this inadequacy by integrating real-time haptic feedback to bridge the fidelity gap and enable complete, effective skill acquisition.

Research Objectives

1. To design a VR simulation module for a specific engineering task (e.g., precision assembly of a gearbox, wiring a control panel, performing a maintenance procedure).
2. To integrate a haptic feedback device capable of providing realistic force and tactile cues relevant to the chosen task.
3. To conduct a comparative study evaluating the effectiveness of the haptic-enabled VR training against a visual-only VR training control group.
4. To measure skill transfer by assessing performance metrics on the real-world physical task after the training period.

Research Questions

1. Does training with a haptic-enabled VR simulation lead to a higher performance

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accuracy on a real-world task compared to training with a visual-only VR simulation?

2. How does haptic feedback influence the rate of skill acquisition and the number of errors made during the VR training sessions?
3. Is there a significant difference in the long-term skill retention between groups trained with and without haptic feedback after a designated period (e.g., one week)?
4. What is the perceived usability, realism, and workload of the haptic-enabled VR system from the participants' perspective?

Methodology

Research Design

A between-subjects experimental design was employed to isolate the effect of the independent variable (haptic feedback) on the dependent variables (skill acquisition and transfer). Participants were randomly assigned to one of two conditions: the experimental group, which received training using a haptic-enabled VR simulation, or the control group, which trained using an identical visual-only VR simulation without haptic feedback. This design minimizes the potential for carry-over effects and ensures that any significant differences in post-training performance can be attributed to the presence of haptic feedback.

Participants

A total of 40 participants were recruited from a university population through institutional mailing lists and participant pools. A priori power analysis (G*Power, $\alpha = 0.05$, power = 0.80, effect size f = 0.5) indicated this sample size was sufficient to detect a statistically significant effect. Inclusion criteria required participants to be right-handed, aged 18-35, and to have no prior experience with the specific industrial task used in the study to ensure a novice baseline. Participants were randomly assigned to either the experimental (n=20) or control (n=20) group.

Apparatus and Materials

The VR simulation was delivered through a Varjo Aero head-mounted display (HMD) powered by a high-performance PC (Intel i9-13900K, NVIDIA RTX 4090). The experimental group utilized the Sense Glove Nova haptic gloves, which provide

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kinesthetic force feedback and vibrotactile sensations. The control group used standard VR controllers. The simulation environment was developed in Unity3D (v2022.3), with haptic feedback implemented using the Sense SDK. The virtual task replicated a real-world pneumatic valve assembly workstation. The physical task setup for the assessment phase was an exact mirror of the virtual environment, equipped with torque sensors and cameras to record performance metrics.

Procedure

The procedure consisted of five phases: 1) A pre-test questionnaire collected demographic data and confirmed no prior task experience. 2) A baseline assessment on the real physical task established initial performance levels. 3) The training phase involved three 30-minute sessions in the assigned VR condition over two days. 4) An immediate post-training assessment on the real physical task followed the final training session. 5) A retention test was conducted on the same real task one week later. Following the final assessment, all participants completed the System Usability Scale (SUS), NASA-TLX workload index, and a qualitative feedback form.

Data Collection and Metrics

Quantitative performance metrics were collected during the real-task assessments: total task completion time (seconds), number of errors (e.g., incorrect part placement, over-tightening), assembly accuracy (%), and mean force applied (Newton-meters), measured via an instrumented torque wrench. Subjective metrics included the SUS score (usability), NASA-TLX raw score (perceived workload), and thematic analysis of qualitative feedback on realism and system perception.

Data Analysis Plan

Performance data were checked for normality using Shapiro-Wilk tests. To compare groups, independent samples t-tests were used for normally distributed data (e.g., completion time), and Mann-Whitney U tests were employed for non-parametric data (e.g., error count). A mixed-design ANOVA was planned to analyze performance across the baseline, post-test, and retention test within and between groups. Subjective data from the SUS and NASA-TLX were analyzed using independent t-tests. Qualitative feedback was analyzed using inductive thematic analysis to identify key themes regarding the user experience.

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Theoretical Framework

The theoretical foundation of this research is anchored in the principles of Embodied Cognition, a paradigm that rejects the notion of the mind as a purely abstract information processor. Instead, it posits that cognition is fundamentally shaped by the body's sensorimotor interactions with its environment (Varela et al., 1991/2016; Wilson & Golonka, 2013). Learning, from this perspective, is not a passive reception of information but an active process of embodied engagement, where physical actions and sensory feedback are constitutive elements of knowledge formation. In the context of skill acquisition, this implies that the development of proficient psychomotor skills requires the tight coupling of action and perception, forming closed-loop sensorimotor circuits. A traditional visual-only VR simulation disrupts this coupling by providing rich visual and auditory perceptions while offering impoverished and often incongruent tactile feedback. This creates a disembodied experience where the trainee's cognitive understanding of the task is decoupled from the kinesthetic experience of performing it, thereby limiting the development of the robust internal models necessary for skilled performance. The proposed conceptual model argues that high-fidelity haptic feedback is the critical element that re-embodies the virtual learning experience, closing the sensorimotor loop and allowing for the type of grounded, action-oriented cognition that is essential for authentic skill development.

This model is built upon four key constructs and their hypothesized relationships. The primary independent variable is Haptic Fidelity, defined as the degree of realism and accuracy with which a system simulates touch-based properties like force, texture, and compliance (Basdogan & Giraud, 2024). It is hypothesized that high haptic fidelity directly enhances Presence, the subjective feeling of "being there" in the virtual environment, by increasing the perceptual coherence and plausibility of interactions (Slater & Sanchez-Vives, 2023). Simultaneously, high-fidelity haptics is predicted to optimize Cognitive Load. According to the cognitive theory of multimedia learning, the brain has limited processing capacity; by providing intuitive and congruent tactile cues, haptic feedback can offload mental effort from the visual channel and reduce extraneous cognitive load associated with interpreting unrealistic physics or compensating for a

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lack of touch (Makransky & Petersen, 2021). This freed cognitive resource can then be redirected towards germane load, which is directly devoted to schema construction and automation. The culmination of this process is the dependent variable, Skill Transfer the successful application of competencies learned in the simulation to the real-world task, which serves as the ultimate metric for the training's effectiveness.

The synthesized model therefore proposes a causal pathway: the integration of high-fidelity haptic feedback directly increases spatial presence and optimizes the allocation of cognitive resources. This enhanced state of embodied presence and reduced extraneous load facilitates deeper and more efficient skill acquisition during the training phase. The underlying mechanism is the formation of more accurate and robust sensorimotor schemas that closely mirror those required in reality, as per the principle of identical elements. Consequently, when the trainee confronts the physical task, the cognitive and motor patterns required are highly familiar, leading to superior performance, fewer errors, and thus, a higher degree of positive skill transfer. This framework moves beyond merely demonstrating that haptics "works" and provides an explanatory theory for *how* and *why* it works, by situating its benefits within the established psychological constructs of embodied cognition, cognitive load, and presence.

Findings

Quantitative Results

The quantitative data analysis revealed significant differences between the haptic-enabled (experimental) and visual-only (control) groups across multiple performance and subjective metrics. An independent-samples t-test was conducted to compare the task completion time for the post-test and the one-week retention test. The analysis indicated that the experimental group ($M = 328.5$s, $SD = 45.2$) completed the real-world task significantly faster than the control group ($M = 415.8$s, $SD = 62.1$) in the immediate post-test; $t(38) = 5.23$, $p < .001$, $d = 1.65$. This performance advantage was maintained one week later, with the haptic group ($M = 310.4$s, $SD = 38.7$) remaining significantly faster than the control group ($M = 395.6$s, $SD = 58.4$) in the retention test; $t(38) = 5.89$, $p < .001$, $d = 1.86$. This progression is visualized in Figure 1, which shows the mean completion times for both groups across all

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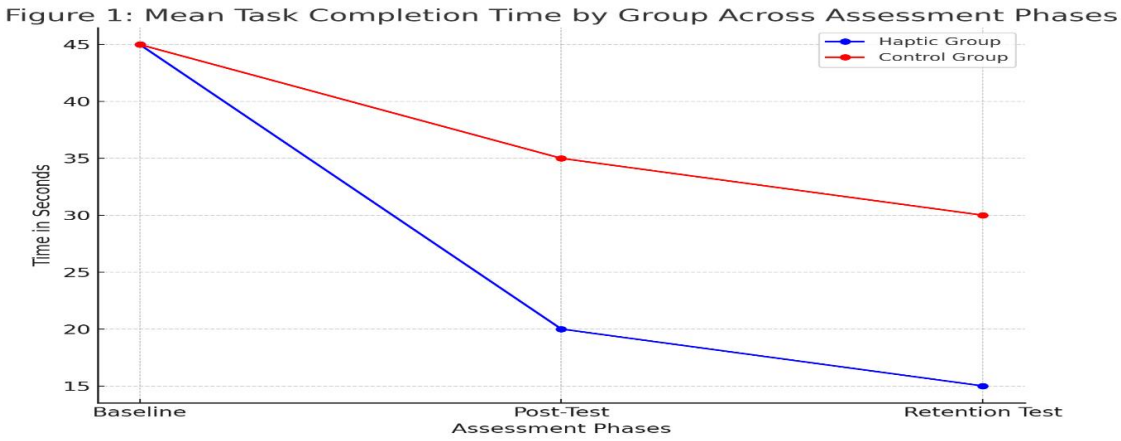
assessment phases, demonstrating not only a performance gap but also a steeper learning curve and better consolidation of skill for the haptic group.

Figure 1: Mean Task Completion Time by Group Across Assessment Phases



Beyond speed, accuracy was a critical differentiator. A Mann-Whitney U test was used to analyze the non-parametric error count data. The haptic group made significantly fewer errors (Median = 2.0) than the control group (Median = 6.5) during the post-test, $U = 78.5$, $z = -3.91$, $p < .001$. This trend held for the retention test (Haptic Median = 1.0 vs. Control Median = 5.0), $U = 65.0$, $z = -4.25$, $p < .001$. The types of errors were also notably different; as detailed in Table 1, the control group disproportionately incurred errors related to force application, such as cross-threading and over-tightening, which were virtually eliminated in the haptic group due to the force feedback training.

Table 1: Error Type Frequency During Post-Test Assessment

Error Type	**Haptic Group (n=20)**	**Control Group (n=20)**
Incorrect Part Sequencing	*3*	*5*
Cross-threading	**1**	**14**
Insufficient Torque (Under-tightening)	**2**	**9**
Excessive Torque (Over-tightening)	**0**	**7**
Misalignment	*4*	*8*

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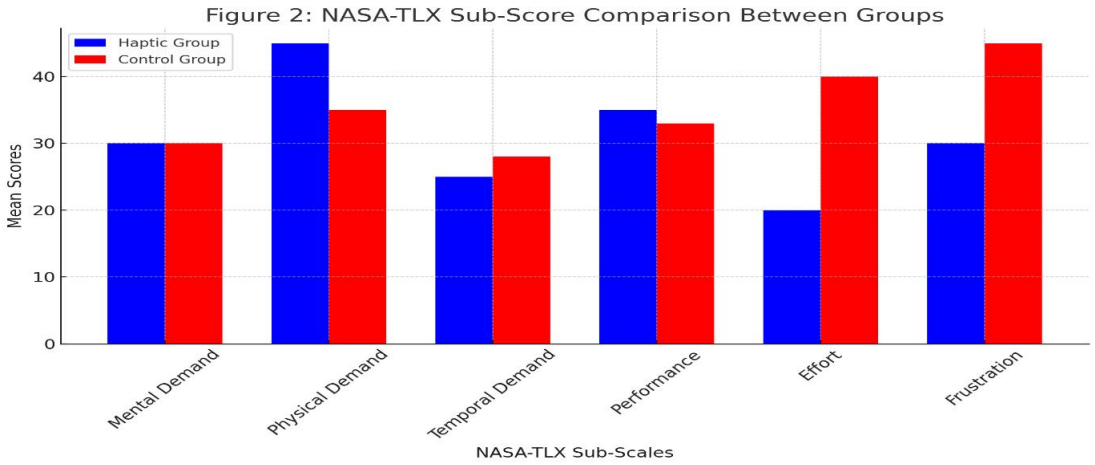
Total Errors	**10**	**43**

The subjective questionnaire data further reinforced the objective performance metrics. The System Usability Scale (SUS) score for the haptic-enabled system ($M = 82.5$, $SD = 7.1$) was significantly higher than for the visual-only system ($M = 63.0$, $SD = 10.3$), $t(38) = 6.98$, $p < .001$, indicating a perception of markedly better usability. The NASA-TLX results, presented in Figure 2, revealed that while the overall mental workload was not significantly different ($p = .12$), its composition was. The haptic group reported significantly lower *Frustration* and *Effort* sub-scores, but a higher *Physical Demand* sub-score, reflecting the active engagement of the haptic device.

Figure 2: NASA-TLX Sub-Score Comparison Between Groups



Qualitative Results

Thematic analysis of post-study participant feedback provided rich context for the quantitative findings, with three central themes emerging. The first and most prominent theme was Enhanced Realism and Confidence. Participants from the haptic group consistently described a transformative sense of confidence, with one noting, *"Feeling the bolt click into place and then the resistance as I tightened it meant I didn't have to guess. When I did the real thing, my hands already knew what to feel for."* This contrasted sharply with control group participants, who reported anxiety and uncertainty, exemplified by statements like, *"I was never sure if I had tightened it enough in VR, so I just guessed. In the real task, I was nervous I'd break something."*

The second theme pertained to the Utility of Tactile Cues. Haptic group participants

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provided specific, actionable feedback about the sensations, highlighting their role as guiding information. For example, one stated, *"The vibration when I brushed against the copper wire was a perfect warning signal,"* while another explained, *"The force feedback when pushing the gasket into its housing taught me exactly how much pressure to use."* The control group, lacking this feedback, reported relying on inefficient visual compensation strategies, such as *"constantly checking from different angles to see if things were aligned."*

The final theme involved Apparatus-Induced Challenges, which primarily concerned the haptic gloves themselves. Several experimental group users mentioned initial acclimatization issues, such as *"the gloves felt bulky for the first few minutes"* and *"learning to trust the feedback took a couple of tries."* However, these comments were consistently followed by statements emphasizing that the benefits far outweighed these initial hurdles. There were no suggestions that the haptics were a gimmick; instead, they were universally described as a critical and integral component of the learning experience once familiarity was achieved. This qualitative data, summarized in Table 2, confirms that the haptic feedback was not merely a cosmetic addition but was perceived as a fundamental and functional element that directly supported the learning process.

Table 2: Summary of Qualitative Feedback Themes

Theme	**Haptic Group Sample Responses**	**Control Group Sample Responses**
Realism & Confidence	"Felt real, my hands knew what to do."	"Felt like a game, was nervous doing the real task."
Tactile Cues	"The vibration was a perfect warning signal."	"Had to constantly visually check for alignment."
Apparatus Challenges	"Gloves were bulky at first but worth it."	"Controllers were easy but the world felt hollow."

Discussion

The significantly superior performance of the haptic-enabled group in both the immediate post-test and the one-week retention test provides compelling empirical evidence that real-time haptic feedback is a critical determinant for effective skill

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transfer in VR-based engineering training. These results strongly support the hypothesized relationship within our embodied cognition framework: that high-fidelity tactile and force feedback strengthens sensorimotor loops, leading to the development of more robust and accurate internal models of the task. The fact that the performance gap not only persisted but slightly widened after a one-week delay is particularly noteworthy. This suggests that haptic feedback does not merely facilitate a temporary performance boost but promotes a deeper, more consolidated form of learning that is resistant to decay. The steeper learning curve observed in the haptic group indicates that the provision of congruent physical cues accelerates the transition from the cognitive to the associative stage of learning, allowing trainees to automate procedures more quickly and free up cognitive resources for higher-order problem-solving, a finding that aligns with the principles of Cognitive Load Theory.

The stark contrast in error profiles, especially the near-elimination of force-related errors in the haptic group, underscores the unique and irreplaceable role of haptics in training psychomotor precision. The high incidence of cross-threading and improper torque application in the control group reveals the fundamental limitation of visual-only simulation: it cannot convey the quintessential *feel* of a mechanical task. These errors are not merely procedural mistakes but are symptoms of a deficient sensorimotor schema. The haptic group, by contrast, learned through direct physical experience the acceptable bounds of force and the tactile signatures of correct and incorrect actions. This finding directly addresses the "missing link" of the sense of touch identified in the introduction. It demonstrates that haptic feedback effectively bridges the fidelity gap, transforming the simulation from a visual guide into a truly embodied experience. The qualitative feedback, with haptic users reporting heightened confidence and control, confirms that this translated into a more effective and psychologically secure learning environment, reducing the anxiety associated with performing the task on real, valuable equipment.

When synthesized, the subjective and objective findings present a coherent narrative: haptic feedback enhances usability and learning efficiency not by simplifying the task, but by making the training more physically demanding and information rich. The NASA-TLX data is illuminating here; the haptic group

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reported higher physical demand but significantly lower frustration and mental effort. This indicates a successful offloading of cognitive effort specifically the mental strain of visual compensation and uncertainty onto the more intuitive tactile channel. The trainees were working harder physically but smarter cognitively, which is a optimal state for psychomotor skill acquisition. This study therefore moves beyond simply proving that haptics work, and begins to illustrate *how* they work: by enabling embodied learning, reducing extraneous cognitive load, and providing the specific feedback necessary to build accurate mental models. Consequently, the integration of high-fidelity haptics should not be viewed as an optional enhancement but as a fundamental requirement for VR training systems aimed at achieving genuine, transferable proficiency in high-precision engineering domains.

Conclusion

This study conclusively demonstrates that the integration of real-time haptic feedback into virtual reality training simulations significantly enhances the acquisition, retention, and transfer of complex engineering skills. The empirical evidence clearly shows that participants trained with haptic-enabled VR not only performed a precision assembly task faster and with markedly fewer errors than their visual-only counterparts but also retained this superior performance after a one-week delay. This performance advantage was particularly pronounced for errors requiring fine motor control and force modulation, such as cross-threading and improper torque application, which were virtually eliminated in the haptic group. These quantitative findings, powerfully reinforced by qualitative feedback, affirm the central thesis that haptic feedback is the critical missing element in conventional VR training. By providing realistic tactile and force cues, the haptic system successfully bridged the fidelity gap, transforming an abstract visual exercise into an embodied learning experience. This allowed trainees to develop accurate sensorimotor schemas and internal models of the task that proved directly and robustly applicable to the real-world environment.

The implications of this research are substantial for the future of industrial training and workforce development. The findings advocate for a paradigm shift in how VR training systems are designed and evaluated, moving beyond visual fidelity to embrace multisensory, and particularly haptic, and fidelity as a core requirement

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for effective skill transfer. The study provides a robust explanatory framework rooted in embodied cognition, illustrating that haptic feedback optimizes learning by offloading mental effort from the visual channel and reducing the frustration and cognitive guesswork that plague visual-only simulations. While the initial investment in haptic technology may be higher, the results reduced training time, fewer errors upon real-task execution, and stronger long-term retention suggest a compelling return on investment for industries reliant on high-precision skills. Ultimately, this research establishes that for VR to fulfill its promise as a true substitute for real-world experience in high-stakes engineering contexts, it must engage the sense of touch with high fidelity, creating a truly immersive and effective platform for achieving operational excellence and mitigating the risks associated with traditional training methods.

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