A breakdown study of a mockup-based consumer haptic setup for virtual reality

# A Breakdown Study of a Mockup-based Consumer Haptic Setup for Virtual Reality

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***Abstract*—Despite the extensive use of visual and audio feedback in Virtual Reality experiences, it is possible to acknowledge a still limited exploitation of haptic devices to recreate the sense of touch, especially at the consumer level. In order to support the high variety of haptic stimuli, commercial off-the-shelf devices may need to be used together, combining separate functionalities into a unique solution and compensating for possibly lacking features of more sophisticated equipment. The present paper moves from the results of a previous study, which analyzed the impact that two haptic setups built using consumer VR gloves and user-prepared props can have on immersive experiences encompassing an active electromechanical tool (precisely, an electric screwdriver). The said study showed that a combined setup, consisting of a pair of vibrotactile gloves and a custom-made mockup of the screwdriver, could be the most effective from many perspectives. It did not isolate, however, the contribution of each setup component to the users' experience. Thus, the current work operates a breakdown analysis of the reference setup by first identifying a set of simpler, downgraded configurations that could be obtained using the original components, and then evaluating their performance-sophistication tradeoff through a new comparative study.**

**TECHNOLOGY ADVANCEMENTS** in the fields of Virtual Reality (VR), computer graphics, and audio synthesis are making computer-generated Virtual Environments (VEs) ever more realistic [1]. Current consumer devices for VR, such as Head-Mounted Displays (HMDs), can already deliver high-quality visual and audio feedback [2]. Nevertheless, there is still the need for Human-Machine Interaction (HMI) products able to provide the users with a complete synesthetic stimulation, which would help to further enhance the sense of immersion and presence in VEs [1]. In this direction, there has been a raising interest

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around devices capable of faithfully delivering haptic stimulation.

The haptic stimuli that the human somatosensory system is able to perceive belong to two main categories: tactile and kinesthetic [1], [3]. Tactile stimuli are associated with the perception of 2D form and local shape (e.g., curvature), as well as textures, light pressure, and vibrations sensed by the skin, whereas kinesthetic stimuli are related to 3D shape identification and to the perception of weight, firm pressure, proprioceptive features, forces and movements sensed at the level of joints, tendons and muscles [3], [4].

Haptic devices developed so far attempt to deliver these stimuli either actively (relying on motors, actuators, and rumblers to actively exert forces on the user) or passively (without actively exerting forces on the user, and rather applying resistance to the user's motion only by exploiting the mechanical properties of materials or friction/braking mechanisms) [5]. Hence, it is common to characterize haptic devices based on the type of feedback they can provide: Active Tactile Feeback (ATF), Active Kinesthetic Feedback (AKF), Passive Tactile Feeback (PTF), and Passive Kinesthetic Feedback (PKF) [3], [6].

Even though, in recent years, an increasing number of haptic devices hit the consumer market [1], [2], the interfaces that are commonly available to most end-users for interacting with VR environments rely on some sort of handheld (or simply hand) controllers. Devices like the HTC Vive wand[1], the Oculus Touch[2], or the Valve Index Knuckles[3], can deliver ATF, e.g., by using vibrations on the palm or the back of the hand, and/or PTF and PKF thanks to their shape and material textures.

With the aim of promoting the mass adoption of VR, the cost of standard hand controllers is maintained relatively low to guarantee affordability [1]. As result, these devices often provide simplified, button-based input functionalities besides basic vibrational ATF and PTF/PKF [1]. Another possible limitation associated with the use of most hand controllers is the need to continuously hold them [2]. This constraint could be critical in scenarios requiring bare-hands interaction, or requesting the user to grab one or more virtual tools during the experience [2].

There are also situations in which operating an appropriate prop that represents the virtual object being manipulated is considered as a more natural interaction solution with respect to hand controllers [7]. This interaction modality can be implemented either by using the real tools as interfaces, or by employing so-called passive haptics, i.e., physical props that surrogate them [8]. In both the cases, the props need to be aligned with their visual counterparts in the VE [9]. For instance, elements such as levers, knobs, buttons and manual tools (e.g., a flashlight or a probe) can be easily approximated using lower-fidelity, passive haptic interfaces provided with six degrees-of-freedom (6-DOF) tracking capabilities [10]. Passive haptics could be also combined with hand controllers to improve fidelity in terms of PTF and PKF [11]. In this case, it may be possible to rely on the tracking offered by the VR system. Nevertheless, mentioned issues possibly affecting the hand controllers would not be solved.

To cope with these issues, hand tracking started to be explored. Optical-based approaches are already integrated in some consumer VR systems (e.g., Meta Quest) or can be implemented using dedicated components (e.g., Leap Motion Controller[4]). Hand tracking-based interfaces could theoretically be advantageous compared to hand controllers. The complete lack of passive haptic feedback, however, may dramatically reduce the perceived naturalness of the interaction [3], [12]. Moreover, the combined use of handheld, passive haptic props is currently impracticable, since visual occlusions caused by the prop would impair optical-based hand tracking functionalities.

Another type of hand tracking-based VR interfaces is represented by haptic gloves. These devices, ranging from costly prototypes to consumer off-the-shelf devices, typically enable free-hand, multi-finger interaction [13]. With respect to haptic capabilities, VR gloves providing both ATF at the fingertips and, more rarely, kinesthetic feedback (AKF and/or PKF), are becoming a reality. Kinesthetic feedback is usually delivered through kinematic structures based on exoskeletons. Gloves provided with these structures, however, show limitations in terms of wearability and encumbrance [14]. To improve the first aspect, one approach is to move the base of the kinematic chain closer to the point of application of the stimulus. If the base is placed too close to the end-effector (e.g., base on a nail, and end-effector on the finger pulp), though, the device can only provide tactile feedback

[1] https://www.vive.com/eu/accessory/controller/

[2] https://www.oculus.com/accessories/quest/

[3] https://www.valvesoftware.com/en/index/controllers

[4] https://www.ultraleap.com/product/leap-motion-controller/

and not the kinesthetic one [14]. The presence of a complex kinematic chain also impacts on the second aspect (i.e., the encumbrance). In fact, these gloves usually adopt a kinematic structure that is different than that of the human fingers and operates externally to the real hand. This is done to avoid the necessity of a precise length calibration of each finger segment and, thus, let the device adapt to the various hand sizes and shapes. The downside is that these devices tend to occupy a certain amount of space around the hand, thus requiring a much larger workspace than actual fingers [14]. This issue could also impair hand-to-hand interactions and virtual objects handling, as well as the manipulation of generically shaped physical props. These limitations do not affect VR gloves provided with finger tracking and ATF-only. These devices do not require articulated structures, and usually fit like normal fabric gloves, thus enabling more natural interactions with both virtual and real elements [10], [15].

From the above review it appears that, despite the advantages offered by full-featured products, when considering possible haptic interfaces for VR interaction it may be reasonable to explore also the possibility to combine, e.g., gloves with other devices like hand controllers or passive haptic props with the final aim of making out the best of each technology while getting rid of associated drawbacks. For instance, in [10], gloves have been used together with passive haptics to deliver both ATF and PKF in manipulation-oriented tasks.

Object manipulation is a common use case for studying haptic interaction in VR. In particular, the literature reports many works that investigated the use of haptic devices to simulate the feedback delivered during the operation of both passive (e.g., screwdrivers, saws, and hammers [16]) and active (e.g., electric screwdrivers and drills [11], [17]) tools. In fact, the simulation of these instruments, commonly used, e.g., in carpentry, could be quite challenging, and require the combined use of different haptic stimuli to enable faithful interactions [18]. The stimulation of AKF/PKF can be of paramount importance for both the tool categories, whereas ATF becomes more relevant for active, electromechanical tools to simulate the vibrations generated by their embedded motors [17].

Moving from the above considerations, the present paper takes some steps forward in the evaluation of haptic configurations for simulating the use of an electromechanical active tool in VR, by building on the findings of a previous study [19]. In that study, two haptic setups based, respectively, on the sole use of an exoskeleton-based, ATF- and PKF-enabled pair of gloves and on the combined use of gloves capable of ATF only plus a user-prepared mockup, were evaluated in terms of user experience (UX), usability, fidelity, presence, cybersickness, task load, and task performance. The evaluation considered the simulation of various phases of a screwing activity performed with an electric screwdriver (ES). This task is a relevant use case for haptic simulation, since the lack of haptic feedback in VR experiences is particularly detrimental to the correct use of this kind of tools compared to real-world operations [12]. For instance, in VR based training scenarios involving assembly operations, haptic stimulation proved to be essential to let the trainees acquire the dexterity required for operating the involved tools [8].

From the evaluation performed in [19], the setup combining the ATF-enabled gloves and the custom-made mockup of the considered tool (used as a handheld prop) prevailed over the use of a single, though more featureful, device. The potentialities of the prevailing setup, however, came at the cost of a higher sophistication of the resulting configuration, and the contribution of its components to the considered dimensions of the users' experience was not investigated. Hence, there might be configurations derived from the combined setup which could be applied to the considered use case and could still guarantee an appropriate trade-off between performance and setup sophistication.

To dig into aspects concerning the delivery of multi-component haptic feedback with the minimum viable hardware, the current work operates a breakdown analysis of the reference setup. This is done by first identifying simpler, downgraded configurations based on its components, and then comparing them with the original design along the previously studied dimensions.

## Related Works

In this section, a categorization of the haptic devices proposed in the literature is first introduced. Afterwards, the focus moves to the haptic simulation of manual tools, both passive and active. Finally, the reference setup is presented and discussed.

### Categorization of Haptic Interfaces

The simulation of haptic stimuli in VR environments has been addressed by previous works in the literature [1], [2], [20], [21]. The authors of [1], in particular, categorized haptic interfaces for VR in five groups: handheld, wearable, physical props, encounter-type and mid-air interfaces. Handheld interfaces are very common, as they encompass the various types of hand controllers bundled with any VR kit (e.g., the Oculus Rift S and HTC Vive Pro, which comprise a HMD and a pair of controllers); they may also be complemented with attachments or add-ons to expand native haptic capabilities. Wearable interfaces consist in devices that are worn on fingers, wrists or hands; according to [13], these devices can be either gloves provided, e.g., with finger tracking capabilities and vibrations, thimbles, in case they have to be worn on the fingertips, or exoskeletons, if they are designed as articulated structures worn on the hands and used to provide PKF or AKF. Physical props are either replicas of real objects or the real objects themselves, and can be physically manipulated to control their digital versions in the VE. Finally, encounter-type and mid-air interfaces indicate respectively, devices providing haptic feedback "on demand" (robotic arms, drones, etc.) and using transducers to deliver ultrasonic ATF through the air.

### Haptic Simulation of Passive Tools

For what it concerns the simulation of passive tools, in [16], a system was proposed in which physical props representing tools such as screwdrivers, saws, and hammers were used to provide haptic stimuli. A physical prop was also used for a virtual working table, in order to better simulate the interaction of the manual tools with it. The main idea of this work was to leverage a redirected, tool-mediated manipulation approach, in which the mapping between physical and virtual tools is distorted to improve the feeling perceived when the physical tool gets in contact with another physical prop. Physical props were tracked using additional sensors (namely, the HTC Vive Trackers). In order to demonstrate the validity of this approach, the authors developed a prototype implementation and ran a user study to evaluate the possibility of recreating the intended sensations. The evaluation included three configurations: Tool+Table, in which both the tool and the table were aligned with physical props; Tool, in which the physical prop was only used for the tool, whereas the table was completely virtual; Controller, in which the tool was aligned with a hand controller, the table was virtual, and the physical props were not employed. The study followed a within-subjects design comparing the three configurations in terms of realism, preference, and precision. The obtained results showed that the first configuration could offer higher levels of realism with respect to using the controller or the physical prop of the tool alone.

In order to provide commercial VR kits with additional haptic feedback, it is possible to design dedicated add-ons for traditional hand controllers, as done in [22]. In that work, the authors designed a partially wearable and partially handheld, fluid-based haptic device capable of simulating both weight and center of gravity through low-cost components. The goals were to demonstrate the possibility of simulating small manual objects like, e.g., hammers, as well as to confirm that the devised device could be easily integrated in common VR systems. To this purpose, a prototype was developed and several subjects were involved in five incremental studies that were carried out to evaluate: i) the minimum weight that can be simulated; ii) how different initial values may affect the minimal perceivable weight; iii) the possibility to simulate different centers of gravity iv) and different objects; v) the usability and effectiveness of using such a device in a VR application. The results of the studies allowed the authors to conclude that: i) small weight variations (lower than 20 g) cannot be perceived when the users hold a hand controller; ii) to simulate a heavier and more noticeable weight it is better to focus on furthering away the mass from the hand in order to create a lever effect; iii) changes in weight are easier to be perceived when simulating long objects than bulky compact objects; iv) variations in weight at 66g/s are acceptable values for gaming applications.

### Haptic Simulation of Active Tools

With respect to active tools, in [17], an interactive drilling simulator for training purposes was proposed. In this case, a mockup of the drill played the role of a passive haptic interface, making the users feel the shape of a conventional drill in their hand. Moreover, various haptic stimuli were delivered through the mockup. More specifically, the simulator supported contact response, machinery vibration, as well as thrust, torsional and edge penetration forces related to the considered task. The purpose of the work was to present the design and the prototype implementation of the simulator. Unfortunately, the results of experimental evaluations were not provided. Nevertheless, a possible limitation of this design could be the need for a physical surface to operate the force detection module and, consequently, to generate the haptic feedback; this would basically prevent any possibility of mid-air use of the mockup in generic VR scenarios not including tracked surfaces.

The above limitation was addressed in [11], where the authors proposed the use of a standard hand controller as a mockup to represent an ES. More specifically, the main objective of this work-in-progress investigation was to evaluate the effect of a mockup when using or not visual guided feedback. The work considered passive haptic stimulation, and explored four alternative setups: realistic, leveraging a controller with the same shape, center of mass and weight of the real tool; grip-force, in which the components of the real tool were mounted on the controller to simulate the shape but not the weight of the real tool (as the typical controller is lighter than the real tool); grip-only, in which the hand controller provided feedback only for the grip part of the tool; the last setup was named virtual, as it only used the controller. Besides passive haptic stimulation, using the controller, it was possible to provide the users with an ATF for the screwing action, while at the same time allowing for mid-air use also in fully intangible VR scenarios. The main limitation of the work was the lack of experimental results, although it was in the authors' plan to compare the four setups with the direct use of the real ES, as the operation considered in the experiment required the users to perform a screwdriving task in wood in both virtual and real settings. Another limitation was the complete absence of hand tracking, which impaired the possibility to put away the mockup and use the hands to interact with the VE.

The authors of [8] investigated the possibility to use consumer haptic devices to simulate a surgical procedure (knee bone drilling) in a serious game. In this case, a non-immersive VR scenario was employed, and two kinesthetic feedback-enabled devices (i.e., Geomagic 3D Touch and Novint Falcon) were compared by means of a preliminary user study. The goal of the study was to evaluate if the haptic feedback provided by the two devices could match the theoretical model adopted to simulate the cortical and cancellous thrust forces during the drilling of a layered bone. According to the authors, preliminary experiments showed that these haptic interfaces could be successfully incorporated into VEs to simulate surgical drilling. The stationary nature and the restricted working area of these devices, however, may represent an obstacle to their employment in room-scale VR scenarios [1].

## Reference Setup

Based on the analysis of relevant literature in the field, the authors of [19] realized that only a few studies considered the possibility to combine passive haptics, hand tracking techniques and consumer devices (supporting tactile and/or kinesthetic feedback) to simulate the use of active manual tools in VR, and even less studies actually evaluated the proposed setups. Hence, they selected one of these tool (specifically, an ES), and ran a user study to investigate possible ways to deliver haptic feedback considering the UX, usability, fidelity, presence, cybersickness, task load, and task performance dimensions. The study analyzed two setups based on consumer VR gloves, consisting respectively of:

- a pair of ATF- and PKF-enabled gloves (SenseGlove DK2), including an exoskeleton that imitates human tendons, also provided with vibrotactile actuators;
- a combination of a simpler pair of gloves endowed with vibration capabilities (Manus Prime X Haptic VR) and a custom-made mockup acting as a prop for the ES, delivering ATF, PTF and PKF.

The mockup used in the second setup was created using a 3D-printed shell representing the handle of the ES and acting as a passive haptic prop; a HTC Vive wand was inserted in the shell to provide 6-DOF tracking, vibrations, and a physical button for the trigger (as done in [11]). The study considered a screwing activity encompassing two different materials (i.e., wood and aluminum), analyzing both subjective and objective aspects. In order to better represent the real-life conditions of this activity, the scenario did not consider the screwing action alone, but also included the grasping, manipulation and positioning of the various elements that had to be screwed together, as well as the grabbing, use and possible release of the simulated ES, as done in similar investigations [23].

The user study was arranged using a within-subjects design. Experimental results showed that the second setup was perceived as more usable and less straining than the first one. No significant differences were found regarding the screwing into the two materials. Moreover, the second setup let the users better perceive the tool's shape and weight, as well as to reach a higher overall task performance, since it allowed them to obtain better ES tip centering accuracy and to reduce the number of slips, the time before and after the first ES interaction, and the screwing time.

These results, however, did not provide insights about the contribution to the users' experience of each of the components of the prevailing setup, or on the possible impact of different configurations based onto them.

## Materials and Methods

Building on the findings obtained in [19], the present paper deals with the mentioned aspects concerning the delivery of multi-component haptic stimulation when simulating active tools in VR and trading for setup sophistication by performing a new study in the form of a breakdown analysis. More specifically, it moves from the setup that provided the best results and compares it with two other configurations obtained by downgrading the original assembly, thus isolating the contribution of its components.

The downgrading consisted in identifying, among the various subsets of the assembly components, the configurations that could be reasonably applied to the original use case. As said, the reference setup, later referred to as *Gloves+Mockup* (G+M), envisaged the use of a pair of ATF-enabled gloves to interact with objects in the VE, in combination with a custom-made mockup of the simulated ES, used as a prop. 6-DOF tracking of the user's wrists was obtained by means of two additional HTC Vive Trackers. In order to track the mockup, another HTC Vive Tracker could have been used, together with a motor (e.g., managed through a micro-controller board) to deliver vibrations. Since both these functionalities could be effectively provided by a common VR hand controller, however, the authors decided to use an HTC Vive wand to this purpose, similarly to what done in [9]. The wand was inserted in a shell acting as a passive haptics: hence, the controller was not used as a direct interface between the user and the VE, but only as part of the physical ES mockup.

### Configurations and Technologies

In the present work, the reference setup was reproduced by leveraging technologies similar to those used in [19] (Figure 1a). In particular, the gloves in the Manus VR Development Kit (DK) [24] were employed, along with a HTC Vive Pro wand mounted on top of a 3D-printed passive haptic prop. As tracking elements for the user's wrists, two HTC Vive Trackers (2018) were also used.

Table 1: Analysis of the reference setup presented in [19], from which the set of new configurations to be tested has been derived. The –* symbol indicates that low-fidelity feedback indirectly provided by the hand controller.

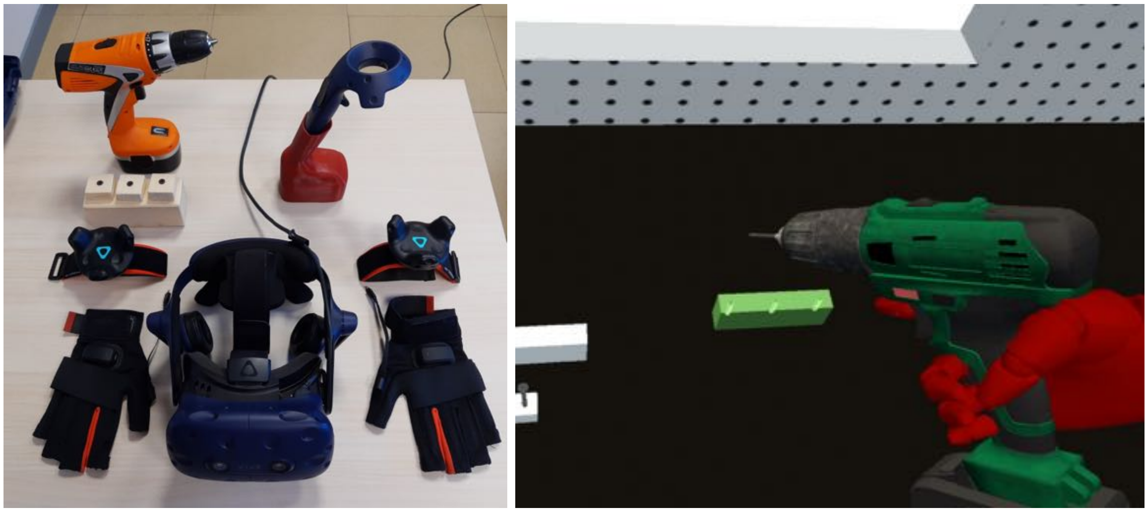
| ES MOCKUP | | | DESCRIPTION | CONFIGURATION |
|---|---|---|---|---|
| 6-DOF TRACKING | ATF | PTF & PKF | | |
| ✓ | ✓ | ✓ | Original configuration | G+M |
| ✓ | ✓ | –* | Removal of the 3D-printed shell | G+C |
| ✓ | – | ✓ | HTC Vive controller does not provide vibrations | Discarded (no reasons to drop vibrational feedback) |
| – | ✓ | ✓ | Original configuration without 6-DOF tracking | Discarded (impossibility to interface the prop with the VE) |
| ✓ | – | –* | Removal of the 3D-printed shell, HTC Vive controller does not provide vibrations | Discarded (no reasons to drop vibrational feedback) |
| – | ✓ | – | Completely virtual ES, vibrations provided via VR gloves | G |
| – | – | ✓ | 3D-printed shell only, no tracking and no vibrations | Discarded (impossibility to interface the prop with the VE) |
| – | – | – | Completely virtual ES, no vibrations provided | Discarded (no reasons to discard vibrational feedback) |

In order to identify the other configurations to be evaluated in the perspective of obtaining setups with reduced sophistication, an analysis of the possible alternatives was performed, whose results are summarized in Table 1.

The first downgraded configuration was obtained by removing from the mockup used in the reference setup the 3D-printed shell; hence, it was named *Gloves+Controller* (G+C). In this configuration, the gloves are still the main interface between the user and the VE, whereas the hand controller serves as a prop for the virtual ES and provides 6-DOF tracking capabilities. In this way, ATF is delivered by both the gloves and the controller, whereas PTF and PKF are delivered only by the controller with lower fidelity with respect to the 3D-printed shell. As for the G+M, the trigger button of the controller is used to mimic the activation button of the virtual ES.

The second downgraded configuration, named *Gloves-only* (G), uses solely the gloves to provide ATF. In this configuration, the physical prop is completely removed. The users have to touch the virtual ES with the hand and partially clench their fist in order to constrain the tool to the hand; then, they can move the ES around, articulate the index finger to operate its activation button, or fully open the hand to drop it on the working table. ATF is used also to signal relevant events (e.g., contact with a virtual object, release of the tool, etc.).

The presence, in each configuration, of VR gloves



(a) Full VR setup and real ES  (b) Simulated VE

Figure 1: Hardware and software used for the experiment.

with finger tracking capabilities was considered as a requirement in [19], since they were needed to support the chosen activity; thus, for the sake of fairness, they were also included in the present work. Finger tracking is exploited to show a virtual representation of the users' hands in the VE, and to allow interaction with objects as needed by grabbing and manipulating them.

### Task

The simulated task was kept mostly unchanged with respect to that in [19], which in turn took inspiration from the screwing activity presented in [11]. Similarly to the reference work, the application was implemented with Unity (2020.3.32f1) and the SteamVR framework (2.7.3).

The user is immersed in a VE representing a garage workshop[5], and placed in correspondence of a working table. Since the G+C and G+M configurations require to interact with physical elements, a real table is aligned with the virtual table for all the configurations. The presence of the real surface allows the user to grab the handheld device from the working table at the beginning of the experience, as well as to put it back when needed.

In [11], the user was requested to tighten four screws, already placed in a vertical position and ready to be screwed in a wooden table. In order to better represent the real-world conditions of a screwing activity, in the present work a manipulation part is added to the experience, as done in [19]. In particular, the user is requested to grab a bar (0.26m $\times$ 0.05m $\times$ 0.04m) that is pre-drilled with three threaded holes, place it in a given spot on the working table, and then tighten a set of three blocks made of the same material (0.04m $\times$ 0.02m $\times$ 0.04m) on it by using three screws of different lengths (30mm, 50mm, and 80mm). Both visual (highlighting) and ATF is employed to facilitate the interaction with these virtual elements. A screenshot of the VE is given in Figure 1b.

An initial "sandbox" training is also employed to let the users familiarize with the VE and relative equipment. In this preliminary experience, the users can try to interact with some virtual objects characterized by different sizes and shapes placed on the working table before performing the actual task.

The simulation supports the reproduction of the haptic feedback for the following phases of the screwing activity:

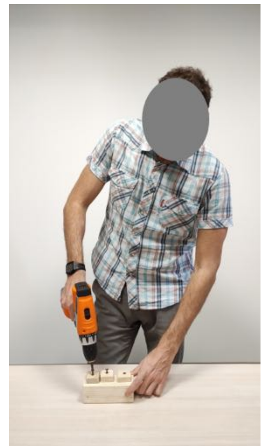
- *Screw head touch* (when the tip of the ES comes in contact with the screw).
- *Screw head slip* (when the tip slips off the screw head).
- *Loose screwing* (when the ES is activated while not in contact with a screw).
- *Screwing* (when the ES is tightening a screw).
- *Screw tightened* (when the ES is kept active while in contact with the screw, but the screw is already completely tightened).

[5]https://assetstore.unity.com/packages/3d/props/interior/simple-garage-197251

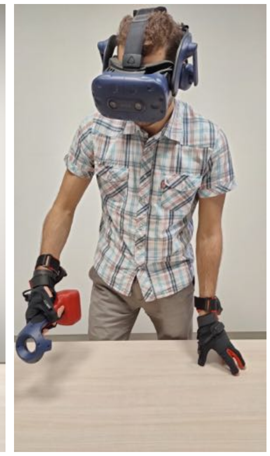
As in [11], the ES must be kept perpendicular to the surface of the screw head to correctly initiate and perform the screwing. If this condition is not maintained while screwing, the applications makes the tip of the ES slip from the screw head.

The reference work considered the screwing in wood and aluminium. These materials, along with rubber, are commonly the target of haptic investigations, being them characterized by different stiffness [25]. Moreover, wood and metal are also two of the most common materials in which real-world screwing is performed [26]. Since in the previous study, however, no significant differences were observed between the two materials, in the present work it was decided to consider only wood for the bar and the gussets.

In order to increase the fidelity of the ATF associated with the simulated ES, vibrations produced by a real ES in the described task were collected with an accelerometer (ADXL345) mounted on the grip of the real ES. Signals related to each screwing phase in the considered material were additionally filtered with a low-pass filter set at 450Hz, which represents the upper-bound for the human sensory system in terms of tactile perception [1], [3].



(a) Real ES



(b) Gloves+Mockup (G+M)

(c) Gloves+Controller (G+C)

(d) Gloves-only (G)

Figure 2: Task considered in the experiments and configurations.

## Experimental Evaluation

This section presents the user study that was arranged to perform the breakdown analysis of the selected configurations.

### Experiment Design

In order to better elicit possible differences among the configurations and minimize confounding factors associated with the expected perceptual variability among the participants, the experiment was arranged following a within-subjects design, following the same procedure used in [19]. Hence, the participants were first requested to experience the procedure described in Section “Task” by operating a real ES and a set of three wooden gussets and screws (Figure 2a). This first phase lets the participants obtain a common reference about the haptic sensations perceived during the task to later compare them with the simulated scenario, thus accounting also for those subjects who may not have any prior experience with a real ES. Then, before being exposed to the simulated ES activity, the participants were allowed to experiment interaction with the VE using the Manus VR gloves in the sandbox scenario. Afterwards, they were asked to perform the task with the three considered configurations (Figures 2b, 2c and 2d). Latin square order of exposition was adopted to counterbalance potential learning effects and minimize possible biases. An a-priori power analysis was performed using the *G*Power* tool [27] to determine the required sample size. Setting $\alpha = 0.05$ and aiming at detecting at least an effect size of medium entity (Cohen’s $f \geq 0.25$), it was found that a sample of 28 participants was adequate to reach a power of $(1 - \beta) = 0.81$ for the arranged study design [28]. The 28 participants were volunteers recruited among the staff and students at the authors’ university (none of them had taken part in the study of [19]). The participants were aged between 21 and 32 ($M = 26.11$ y.o., $SD = 2.78$ y.o.); 75% were males, 25% females.

Table 2: Objective results

| Metric | [unit] | Average (Confidence Interval) | | | *p*-value (Cohen's *d*) | | | |
|---|---|---|---|---|---|---|---|---|
| | | *G* | *G+C* | *G+M* | *Friedman* | *G /G+C* | *G /G+M* | *G+C /G+M* |
| ES tip centering accuracy | [mm] | 8.87 (1.65) | 7.23 (0.74) | 7.31 (0.78) | 0.114 | – | – | – |
| Number of slips | [#] | 2.43 (0.81) | 1.18 (0.57) | 1.32 (0.48) | 0.054 | – | – | – |
| Grabbing time before first ES interaction | [s] | 2.64 (0.48) | 2.43 (0.32 | 2.33 (0.25) | 0.381 | – | – | – |
| Grabbing time after first ES interaction | [s] | 2.22 (0.29) | 2.20 (0.21) | 2.33 (0.21) | 0.156 | – | – | – |
| Time elapsed at screw tightened | [s] | 1.13 (0.35) | 0.54 (0.04) | 0.52 (0.04) | <**0.001** | <**0.001** (0.93) | <**0.001** (0.95) | 0.350 (0.16) |

### Subjective and Objective Metrics

Like in the reference work, a number of objective measures were automatically collected within the VR experience: the accuracy related to the centering of the screw head with the tip of the ES, the time spent while manipulating virtual objects, the time spent on each of the phases, and the number of times the tip of the ES slipped out of the screw head.

Similarly, for the subjective evaluation the questionnaire exploited in [19] was used. The questionnaire was organized in the following sections:

- Before Experience Questionnaire (BEQ), administered before the screwing activity with the real ES, including questions concerning demographics, previous knowledge about the operation of a real ES, and expertise with the used technologies.
- Post-Real ES Questionnaire (RESQ), administered after the screwing activity with the real ES but before the exposition to the sandbox VE, evaluating to what extent the participants were able to discern among the various haptic sensations related to the use of the real tool; a pre-experience Simulator Sickness Questionnaire [29] (pre-SSQ) was also included in this section.
- After Experience Questionnaire (AEQ), administered after the three configurations were experienced, designed to assess the remaining dimensions of interest for the activity; this section included four standard tools, i.e., System Usability Scale questionnaire (SUS) [30], SIM-TLX [31] for the task load, UEQ [32] for the UX, and two sections of the VRUSE [33] for fidelity and presence, followed by a second post-experience iteration of the SSQ (post-SSQ) and an ad-hoc section to directly compare the three configurations by asking the participants to rank them along several relevant dimensions.

At the end, open feedback from the participants was gathered as well.

## Results

The statistical significance of the results was analyzed by performing the Friedman test ($p$-value $\leq$

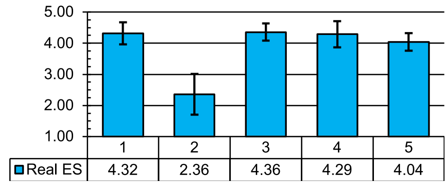



Figure 3: RESQ results. By relying on haptic sensations felt: #1. I felt the contact with the screw head; #2. It felt different screwing screws of different lengths; #3. I felt when screw was tightened; #4. I felt when screw head slipped; #5. I was able to distinguish the different phases of the screwing activity in the wood;

$0.05$) with the Wilcoxon signed-ranks test as post-hoc.

Comparing the information collected through the BEQ with that of [19], no statistical difference was found for any of the considered aspects.

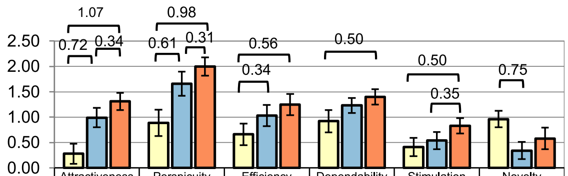
Considering the present sample, $57.0\%$ of participants had never or just rarely used an HMD, whereas $43.0\%$ of them stated to use immersive VR technologies quite often. Moreover, $35.0\%$ of participants had never or seldom used a real ES, whereas $65.0\%$ of them were moderately to very familiar with it.

For what it concerns the haptic sensations perceived when operating the real ES, analyzed through the RESQ (Figure 3), the only feature that was barely noticeable pertained the ability to discern the screws' length by just relying on haptic stimuli.

With respect to the objective data collected during the experiments (Table 2), no significant differences were observed for most of the metrics, except for the time needed to recognize that the screws were fully tightened. In particular, when using the G configuration, the operation required more time compared to the other configurations.

Regarding cybersickness, no significant differences were observed for any of the pre-/post-SSQ indicators.

Based on the outcomes of the SUS ($M_G = 62.23$, $M_{G+C} = 74.11$, $M_{G+M} = 76.70$, $CI_G = 7.90$, $CI_{G+C} = 4.61$, $CI_{G+M} = 4.42$, $p$-value $< 0.001$), the G configuration was perceived as significantly less usable than both the G+C ($p$-value $= 0.003$, $d = 0.71$)




| | Attractiveness | Perspicuity | Efficiency | Dependability | Stimulation | Novelty |
|---|---|---|---|---|---|---|
| G | 0.28 | 0.89 | 0.66 | 0.92 | 0.41 | 0.96 |
| G+C | 0.99 | 1.66 | 1.03 | 1.23 | 0.54 | 0.34 |
| G+M | 1.31 | 2.00 | 1.25 | 1.40 | 0.83 | 0.58 |

Figure 4: Subjective results based on the UEQ. Baffles are used to report significant differences with *p*-value $\leq 0.05$ together with the associated effect size (Cohen's $d$).

and the G+M one ($p$-value $< 0.001$, $d = 0.88$).

Regarding the UX, the results of the UEQ are reported in Figure 4. Considering statistically significant differences, the participants judged the G+M as the most attractive and perspicuous configuration, followed by the G+C and G ones, respectively. The G configuration was perceived as the least efficient among the three, whereas the G+M resulted to be the best configuration in terms of stimulation. The G+M configuration was also perceived as significantly more dependable than the G one. As expected, the G+C configuration (which is based on a more traditional use of the hand controller) was considered as less novel than the G one (i.e., an interaction method based only on the use of hand tracking and ATF), whereas no significant differences were observed regarding the G+M configuration with respect to the other two.

The reasons behind these outcomes regarding UX can be inferred from the results of the other sections of the questionnaire, which are discussed hereafter. In particular, focusing on statistically significant differences in the SIM-TLX section (Figure 5), it can be observed that the G+M configuration was perceived as less mentally demanding and frustrating than the other two. Moreover, when using the G configuration, the participants reported more difficulties in controlling the tool during the execution of the task than when using the G+M one. These results may be partially related to the functioning of the grabbing logic with the G configuration. In fact, in the case of the G+C and G+M configurations, the tool was aligned with a physical object that can be handled like its real counterpart. On the contrary, with the G configuration, the participants had to perform a number of actions (e.g., grab the virtual tool and operate its trigger while holding it) with a totally intangible object, and the lack of passive haptic feedback could have made this activity particularly difficult and tedious. The absence of significant differences between G and G+C may indicate that the major contribution should be ascribed to the presence of the mockup.

Regarding the usability factors evaluated through the VRUSE questionnaire (Figure 6), the participants reported the highest appreciation for the input method when operating with the G+M configuration, and the lowest appreciation in the case of G configuration. Regarding the simulation fidelity in terms of visual, aural and haptic feedback, the participants were generally more satisfied with the simulation when using both G+C and G+M than the G one. Significant differences between the G+M and G configurations were also observed considering presence, and the G+M resulted to be the best one in terms of satisfaction.

Looking at the results of the ad-hoc section (Table 3, analyzed dimensions in the caption), it is possible to note that the G configuration was considered as the less comfortable, even though it does not require any physical object to be held; this outcome was probably due to the particularly clunky interaction paradigm required to grab and use the non-physical ES. As expected, a clear rank between the three configurations cannot be observed for what it concerns the naturalness of the manipulation of the wooden equipment (bar and blocks), since interaction resorted to the gloves for all the configurations. The G+M was also judged as the configuration enabling the best interaction with the virtual ES, as well as the one characterized by the highest fidelity of the ES handle's shape; the G configuration, in turn, was judged as the worst for the same aspects. Interestingly, no statistically significant differences were observed regarding the provision of a ATF similar to that of a real ES, possibly indicating that the three configurations are equivalent for the rendering of this kind of haptic feedback. Despite this outcome, the G+M configuration appeared to allow the participants to perceive more faithfully the screwing of screws with different lengths; it also allowed the participants to perceive the screw tightening status and the screw head slip better than the G configuration. Finally, the G+C and G+M configurations allowed the participants to experience a higher sense of control over the task, and provided them with a higher sense of efficiency with respect to the G configuration. Regarding the overall preference, the G+M was judged as the best configuration, followed by G+C and G.

The results regarding the G configuration may be

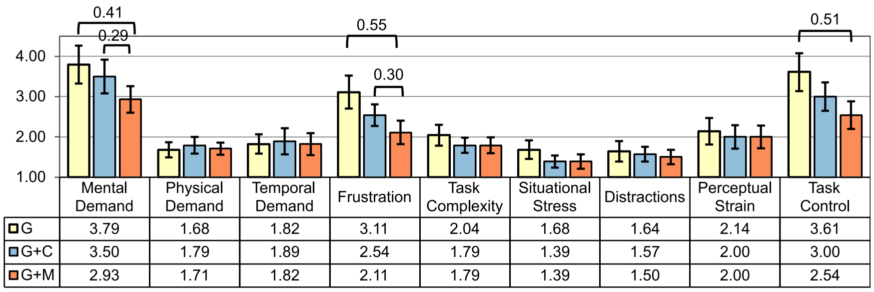



Figure 5: Subjective results based on the SIM-TLX. Baffles are used to report significant differences with $p$-value $\leq 0.05$ together with the associated effect size (Cohen's $d$).

Table 3: Subjective ranking of configurations (ad-hoc).

| Item | Question | Rank (Median) | | | *p*-value (Cohen's *d*) | | | |
|---|---|---|---|---|---|---|---|---|
| | | *G* | *G+C* | *G+M* | *Friedman* | *G/G+C* | *G/G+M* | *G+C/G+M* |
| #1 | Which configuration is more comfortable to a sustained use? | 3 | 2 | 1 | **0.001** | **0.010** (0.89) | <**0.001** (1.26) | 0.204 (0.34) |
| #2 | Which configuration lets you feel more natural manipulating bars and blocks? | 1 | 1 | 1 | 0.373 | - | - | - |
| #3 | Which configuration allows you to better interact with the virtual ES? | 3 | 2 | 1 | <**0.001** | <**0.001** (1.55) | <**0.001** (2.89) | **0.003** (1.07) |
| #4 | Which configuration gives you a more faithful feedback of the real ES handle's shape? | 3 | 2 | 1 | <**0.001** | <**0.001** (3.88) | <**0.001** (8.28) | <**0.001** (2.51) |
| #5 | Which configuration gives you a vibrational feedback closer to the real ES? | 3 | 2 | 1 | 0.121 | - | - | - |
| #6 | Which configuration allows you to better perceive your hands' and fingers' position/tracking? | 3 | 2 | 1 | **0.001** | **0.003** (1.07) | **0.003** (1.16) | 0.579 (0.16) |
| #7 | Which configuration gives you a more faithful feedback of the ES's activation button? | 3 | 2 | 1 | <**0.001** | <**0.001** (1.70) | <**0.001** (2.82) | **0.013** (0.79) |
| #8 | Which configuration lets you more faithfully perceive screwing in the wood? | 3 | 2 | 1 | **0.004** | **0.004** (0.92) | **0.011** (0.98) | 0.686 (0.11) |
| #9 | Which configuration lets you more faithfully perceive the contact with the screw head? | 3 | 2 | 1 | 0.129 | - | - | - |
| #10 | Which configuration lets you more faithfully perceive differences in screwing screws with different lengths? | 2 | 2 | 1 | **0.008** | 0.259 (0.22) | **0.037** (0.70) | **0.049** (0.53) |
| #11 | Which configuration lets you more faithfully perceive the screw tightening status? | 3 | 2 | 1 | **0.069** | 0.340 (0.26) | **0.026** (0.70) | 0.068 (0.53) |
| #12 | Which configuration lets you more faithfully perceive the screw head slip? | 3 | 1 | 1 | **0.042** | 0.059 (0.55) | **0.001** (0.81) | 0.281 (0.28) |
| #13 | Which configuration lets you better distinguish the different phases of screwing in the wood? | 2 | 2 | 1 | 0.113 | - | - | - |
| #14 | Which configuration allows you to experience a higher sense of control over the task? | 3 | 2 | 1 | <**0.001** | <**0.001** (1.35) | <**0.001** (1.93) | 0.123 (0.53) |
| #15 | Which configuration allows you perform the task with higher efficiency? | 3 | 2 | 1 | <**0.001** | **0.002** (1.43) | <**0.001** (2.10) | 0.142 (0.48) |
| #16 | Which configuration do you prefer (overall)? | 3 | 2 | 1 | <**0.001** | **0.005** (0.94) | <**0.001** (1.81) | **0.024** (0.76) |

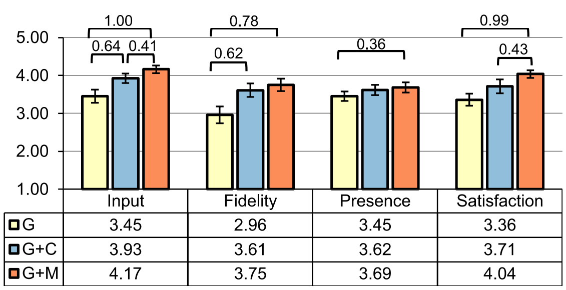



Figure 6: Subjective results based on the VRUSE. Baffles are used to report significant differences with $p$-value $\leq 0.05$ together with the associated effect size (Choen's $d$).

also related to a hardware limitation of the employed VR gloves. In fact, like in the reference work, the Manus VR DK used for the experiment allowed a 6-DOF tracking by means of additional tracking elements positioned on the user's wrists. The 3-DOF Inertial Measurement Unit (IMU) of the gloves, however, suffered from a considerable drift over time [34], frequently causing a rotational misalignment between the virtual hands and the real counterparts. This issue may have been mitigated by the presence, in G+C and G+M, of the hand controller, which guaranteed the correct alignment of the virtual ES even in case of hand misalignments.

The limited tracking performance of the hand's orientation also emerged from the open feedback section of the questionnaire, where some participants lamented a slight but visible misalignment of their hands. Still regarding open feedback, few participants pointed out that the ATF was perceived as appreciably less intense with the G+M configuration than with the G+C one, suggesting that the mockup may have a dampening effect on the generated vibrations. Moreover, one participant said to have relied much more on the ATF with the G configuration than with the other two configurations, being it the only form of haptic feedback available during the simulation.

## Conclusions and Future Work

This paper presented a breakdown study of a VR gloves-based combination of consumer haptic devices that, in a previous study regarding the simulation of an active carpentry tool (precisely, an ES) [19], proved to be capable of performing better when compared with a single, fully-fledged product.

The aim of the new experiment was to evaluate, in terms of UX, usability, fidelity, presence, cybersickness, task load, and task performance, two configurations obtained by downgrading the original setup, thus considering the possible impact of a reduced setup sophistication. The evaluation, which followed the methodology adopted in [19], included the original setup, i.e., a combination of ATF-enabled VR gloves and a passive haptic-based mockup (G+M), a gloves-only configuration (G), and the use, along with the gloves, of a hand controller as a prop (G+C).

Experimental results showed, for the considered scenario, the superiority of the prop-based configurations (G+C and G+M) with respect to the G one for various relevant dimensions regarding, e.g., attractiveness, perspicuity, efficiency, input, comfort, interaction, overall fidelity, passive haptic fidelity (PTF and PKF), control, and overall preference. The G+M configuration also prevailed, with respect to the G one, in terms of core aspects such as dependability, stimulation, presence, satisfaction, mental demand, frustration, and task control (SIM-TLX), as well as in some ad-hoc indicators regarding the perception of the different phases of the screwing action and of the actual fingers' and hand's position. Moreover, the original mockup-based configuration (G+M) also scored better than the G+C one on aspects like attractiveness, perspicuity, stimulation, input, satisfaction, mental demand, frustration, interaction, shape and passive haptic fidelity, as well as on the mentioned indicators related to the screwing action and the overall preference. Finally, the only feature of the G configuration that was recognized as a strength, with respect to G+C one, was the possibility to interact in VR using only the hands, probably because the use of the hand controller as a prop was perceived as very similar to the classic use of the device as pure hand interface.

Interpreting the obtained results in terms of breakdown analysis, it can be said that:

- the use of a physical prop (G+C or G+M) in place of the sole gloves (G) positively impacts on mental demand, frustration, attractiveness, perspicuity, efficiency, input, fidelity (VRUSE), comfort, interaction, passive haptic fidelity (PTF and PKF), fidelity of the various elements (i.e., hand's and fingers's tracking, feedback of the ES trigger, and various phases of the screwing action), control, efficiency, and overall preference;
- if the physical prop is also provided with an higher-fidelity passive haptic component, like the 3D-printed shell of the ES (G+M), a further benefit in terms of task control (SIM-TLX), attractiveness, perspicuity, dependability, simulation, input, presence, satisfaction, interaction, passive haptic fidelity, fidelity of the ES trigger, and overall preference is observed;
- the sole employment of the standard hand controller as a prop (G+C) negatively affects the perceived novelty of the setup with respect to the absence of props (G).

Despite the poorer scoring of the G+C configuration with respect to the G+M one, the former occupies an intermediate position between the three: this aspect suggests that it could still represent a good compromise between setup sophistication and performance for the various evaluated dimensions.

A potential limitation about the findings may be related to the close similarity between the shape of the simulated tool's (the ES's) handle and the hand controller. When simulating other active tools markedly different from the controller (in terms of shape and weight), the G+C configuration may lose an edge over the other two. This limitation was not affecting the study in [19], since the controller was only used to provide the mockup with 6-DOF tracking capabilities, vibrations, and a physical trigger for the ES, while the perceived shape was reproduced through the 3D-printed shell. Hence, it may be worth to extend the analysis to other active tools.

Another potential limitation could be related to the choice of the VR gloves since, as said, the selected product was found to be characterized by poor tracking performance in terms of hand orientation. Manus' developers were probably aware of this issue since, in the most recent iteration of the device, the mounting for the HTC Vive Tracker has been moved from the wrist to the back of the hand, thus overriding the IMU-based orientation. Hence, other gloves may be also investigated.

Lastly, future work could also consider the extension of the current evaluation to other technologies supporting VR interactions (possibly based on the combination of different consumer devices), and the inclusion of further relevant scenarios (e.g., simulating active tools with different physical props, or the operation of the ES as part of more complex carpentry tasks).

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## REFERENCES

1. C. Wee, K. M. Yap, and W. N. Lim, "Haptic interfaces for virtual reality: Challenges and research directions," *IEEE Access*, vol. 9, pp. 112 145–112 162, 2021.
2. E. Bouzbib, G. Bailly, S. Haliyo, and P. Frey, "'Can I touch this?': Survey of virtual reality interactions via haptic solutions," in *Proc. 32e Conférence Francophone sur l'Interaction Homme-Machine*, 2021, pp. 1–16.
3. K. S. Hale and K. M. Stanney, "Deriving haptic design guidelines from human physiological, psychophysical, and neurological foundations," *IEEE Computer Graphics and Applications*, vol. 24, no. 2, pp. 33–39, 2004.
4. J.-L. Rodríguez, R. Velázquez, C. Del-Valle-Soto, S. Gutiérrez, J. Varona, and J. Enríquez-Zarate, "Active and passive haptic perception of shape: Passive haptics can support navigation," *Electronics*, vol. 8, no. 3, p. 355, 2019.
5. A. Zenner and A. Krüger, "Shifty: A weight-shifting dynamic passive haptic proxy to enhance object perception in virtual reality," *IEEE Transactions on Visualization and Computer Graphics*, vol. 23, no. 4, pp. 1285–1294, 2017.
6. M. White, J. Gain, U. Vimont, and D. Lochner, "The case for haptic props: Shape, weight and vibro-tactile feedback," in *Motion, Interaction and Games*, 2019, pp. 1–10.
7. B. Boos and H. Brau, "Erweiterung des UEQ um die dimensionen akustik und haptik," in *Mensch und Computer 2017 - Usability Professionals*, S. Hess and H. Fischer, Eds. Regensburg: Gesellschaft für Informatik e.V., 2017.
8. M. Nguyen, M. Melaisi, B. Cowan, A. J. Uribe Quevedo, and B. Kapralos, "Low-end haptic devices for knee bone drilling in a serious game," *World Journal of Science, Technology and Sustainable Development*, vol. 14, no. 2/3, pp. 241–253, 2017.
9. R. D. Joyce and S. Robinson, "Passive haptics to enhance virtual reality simulations," in *Proc. AIAA Modeling and Simulation Technologies Conference*, 2017, pp. 1–10.
10. D. Calandra, F. G. Pratticò, A. Cannavò, L. Micelli, and F. Lamberti, "Building reconfigurable passive haptic interfaces on demand using off-the-shelf construction bricks," in *Proc. IEEE Conference on Virtual Reality and 3D User Interfaces*, 2019, pp. 1403–1404.
11. M. Jeong, S. Lim, T. Lim, and J. Ryu, "Work-in-progress–Is virtual reality simulation ineffective for skill acquisition training?" in *Proc. 7th International Conference of the Immersive Learning Research Network (iLRN)*, 2021, pp. 1–3.
12. P. Fratczak, Y. M. Goh, P. Kinnell, L. Justham, and A. Soltoggio, "Virtual reality study of human adaptability in industrial human-robot collaboration," in *Proc. IEEE International Conference on Human-Machine Systems (ICHMS)*, 2020, pp. 1–6.
13. J. Perret and E. B. Vander Poorten, "Touching virtual reality: A review of haptic gloves," in *Proc. 16th International Conference on New Actuators*, 2018, pp. 1–5.
14. D. Wang, M. Song, A. Naqash, Y. Zheng, W. Xu, and Y. Zhang, "Toward whole-hand kinesthetic feedback: A survey of force feedback gloves," *IEEE Transactions on Haptics*, vol. 12, no. 2, pp. 189–204, 2019.
15. S. Lontschar, D. Deegan, I. Humer, K. Pietroszek, and C. Eckhardt, "Analysis of haptic feedback and its influences in virtual reality learning environments," in *Proc. 6th International Conference of the Immersive Learning Research Network (iLRN)*, 2020, pp. 171–177.
16. P. L. Strandholt, O. A. Dogaru, N. C. Nilsson, R. Nordahl, and S. Serafin, "Knock on wood: Combining redirected touching and physical props for tool-based interaction in virtual reality," in *Proc. CHI Conference on Human Factors in Computing Systems*, 2020, pp. 1–13.
17. D.-S. Choi, S. Ryu, Y. Do, K.-U. Kyung, K. Jin, and S.-Y. Kim, "Affordable drilling interface for haptic interaction in virtual environment," in *Proc. IEEE International Conference on Consumer Electronics (ICCE)*, 2019, pp. 1–2.
18. J. Jose, R. Unnikrishnan, D. Marshall, and R. R. Bhavani, "Haptics enhanced multi-tool virtual interfaces for training carpentry skills," in *Proc. 2016 International Conference on Robotics and Automation for Humanitarian Applications (RAHA)*, 2016, pp. 1–6.
19. F. G. Pratticò, D. Calandra, M. Piviotti, and F. Lamberti, "Assessing the user experience of consumer haptic devices for simulation-based virtual reality," in *Proc.*

*11th International Conference on Consumer Electronics (ICCE-Berlin)*, 2021, pp. 1–6.
20. D. Escobar-Castillejos, J. Noguez, L. Neri, A. Magana, and B. Benes, “A review of simulators with haptic devices for medical training,” *Journal of Medical Systems*, vol. 40, no. 4, p. 104, 2016.
21. D. Wang, K. Ohnishi, and W. Xu, “Multimodal haptic display for virtual reality: A survey,” *IEEE Transactions on Industrial Electronics*, vol. 67, no. 1, pp. 610–623, 2020.
22. D. Monteiro, H.-N. Liang, X. Wang, W. Xu, and H. Tu, “Design and development of a low-cost device for weight and center of gravity simulation in virtual reality,” in *Proc. International Conference on Multimodal Interaction*, 2021, pp. 453–460.
23. S. Kind, A. Geiger, N. Kießling, M. Schmitz, and R. Stark, “Haptic interaction in virtual reality environments for manual assembly validation,” *Procedia CIRP*, vol. 91, pp. 802–807, 2020, enhancing design through the 4th Industrial Revolution Thinking.
24. M. Caeiro-Rodríguez, I. Otero-González, F. A. Mikic-Fonte, and M. Llamas-Nistal, “A systematic review of commercial smart gloves: Current status and applications,” *Sensors*, vol. 21, no. 8, p. 2667, 2021.
25. A. Okamura, M. Cutkosky, and J. Dennerlein, “Reality-based models for vibration feedback in virtual environments,” *IEEE/ASME Transactions on Mechatronics*, vol. 6, no. 3, pp. 245–252, 2001.
26. C. H. Leong, R. Mohd-Mokhtar, N. S. Ahmad, and C. W. Leow, “Modeling and control of torque and impact rate during screwing process,” in *Proc. IEEE Region 10 Conference*, 2017, pp. 1997–2002.
27. F. Faul, E. Erdfelder, A. Buchner, and A.-G. Lang, “Statistical power analyses using G* Power 3.1: Tests for correlation and regression analyses,” *Behavior Research Methods*, vol. 41, no. 4, pp. 1149–1160, 2009.
28. J. Cohen, *Statistical power analysis for the behavioral sciences*. Routledge, 2013.
29. R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, “Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness,” *The International Journal of Aviation Psychology*, vol. 3, no. 3, pp. 203–220, 1993.
30. J. Brooke, “SUS: A ‘quick and dirty’ usability scale,” *Usability Evaluation in Industry*, p. 189, 1996.
31. D. Harris, M. Wilson, and S. Vine, “Development and validation of a simulation workload measure: The simulation task load index (SIM-TLX),” *Virtual Reality*, vol. 24, no. 4, pp. 557–566, 2020.
32. B. Laugwitz, T. Held, and M. Schrepp, “Construction and evaluation of a user experience questionnaire,” in *HCI and Usability for Education and Work*, A. Holzinger, Ed. Berlin, Heidelberg: Springer Berlin Heidelberg, 2008, pp. 63–76.
33. R. S. Kalawsky, “VRUSE – A computerised diagnostic tool: For usability evaluation of virtual/synthetic environment systems,” *Applied Ergonomics*, vol. 30, no. 1, pp. 11–25, 1999.
34. C. Mizera, T. Delrieu, V. Weistroffer, C. Andriot, A. Decatoire, and J.-P. Gazeau, “Evaluation of hand-tracking systems in teleoperation and virtual dexterous manipulation,” *IEEE Sensors Journal*, vol. 20, no. 3, pp. 1642–1655, 2019.

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