Study on the Influence of Upper Limb Representations and Haptic Feedback in Virtual Reality

Natalie Hube*
Mercedes-Benz AG
University of Stuttgart

Alexander Achberger†
Mercedes-Benz AG
University of Stuttgart

Philipp Liepert‡
Mercedes-Benz AG

Jonas Vogelsang§
Mercedes-Benz AG

Krešimir Vidačković¶
Hochschule der Medien - University of Applied Science

Michael Sedlmair‖
University of Stuttgart

ABSTRACT

Visual representations are used in various digitization processes to display objects in immersive environments. In industrial environments, the self-representation can be very helpful when reviewing 3D models to conform realistic proportions, particularly in combination with haptic feedback that goes beyond vibrating controllers. For instance, haptic feedback in combination with a virtual representation supports working on use cases where collision is an important part to maintain data quality. To understand the dependency of both, we conducted a pilot study with 15 users from the automotive sector to examine the influence of upper limb representations on haptic feedback in Virtual Reality. Each participant was assigned with one of three upper limb representations which was used in different scenarios using haptic feedback devices. Overall, we found that the realistic arm representation was rated highest in terms of perceived realism and achieved the best task performance.

Keywords: virtual reality, avatars, haptic feedback

Index Terms: Human-centered computing—Interaction devices—Haptic devices; Human-centered computing—Interaction paradigms—Virtual reality; Human-centered computing—HCI design and evaluation methods—User studies;

1 INTRODUCTION

Since the rise of the internet of things [17], engineering processes in the automotive sector are implemented with new digital technologies, such as Virtual Reality (VR) [42], to reduce hardware costs and identify potential risks as soon as possible. VR is used for a wide range of tasks, from engineering processes to hazard training, many processes can be simulated. Some engineering processes in the automotive sector already rely on VR as a display medium [1, 9, 29]. These processes include assembly planning, data investigation or construction feasibility [3]. In these applications users are displayed with different visual representations, in terms of representation fidelity as well as anthropomorphism. Some of these applications use abstract forms to display hand movement, others focus on realistic hand and arm representations.

As of today, various VR applications for assembly investigation, photo-realistic visualization, and ergonomic surveys exist [5, 10]. These applications focus on the display of real objects, the self-representation in the virtual world is a secondary thought and, thus, often overlooked. Though, a self-representing human body can have a positive influence on haptic perception [34]. Many ways exist to visualize upper limbs in VR, from very abstract shapes up to highly realistic representations [4], however, it is unknown if the representation affects the perception of haptic feedback.

Research is also engaged with the usage of haptic feedback to increase immersion in the virtual environment [11, 20]. Still, haptic feedback is rarely used in engineering VR tools [6], although hands are used to interact with virtual objects and surroundings in virtual environments. Self-representing upper limbs used with haptic feedback could bridge the gap between the virtual and real environment. Haptic feedback comes in many different forms. Most common is the vibro-haptic feedback most controllers offer. However, vibrotactile feedback is not suitable for all VR use cases. For example, the simulation of collisions is important for industrial VR use cases, where kinesthetic feedback devices are necessary. Kinesthetic feedback devices stop users' movements to support the engineers when they are colliding, such as by assembling car components. To support engineers with suitable haptic feedback, different devices were developed, such as string-based devices [1, 32], bodysuit systems [21] or mechanical arms [13].

In this paper, we focus on the influence of different upper limb representations used within virtual environments using scenarios from the automotive sector. We conducted an expert user study with 15 participants from the automotive industry to find out, whether the self-representation influences the experience of perceiving haptic feedback. Further, we investigate, whether the self-representation influences the task execution and which representation is overall preferred by users. We found evidence that participants preferred the realistic arm representation and were quicker completing tasks. Further, participants stated that the perception of haptic feedback was increased by the realistic arm representation compared to the ghost hand and realistic hand. Additionally, we found that participants using the realistic arm felt more competent during the user study.

2 BACKGROUND & RELATED WORK

Our work primarily focuses on examining the effect of users upper limb representations on the perception of haptic feedback in an overall VR experience.

2.1 Haptic Feedback for Industrial Environment

One way to achieve immersion in VR is to integrate haptic feedback. As objects in VR do not exist in the real world, the stimulation of grabbing or colliding with objects is missing. Common VR systems provide haptic feedback through vibration in handheld controllers which is limited in simulating various kinds of haptic stimuli. In industrial environments, most of the haptic stimuli that engineers need for their use cases cannot be simulated by vibrotactile feedback alone. Some industrial use cases require collision simulation on multiple body parts, such as head or elbow, which systems like INCA 6D [32] do not support. STRIVE [1] is a string-based haptic feedback device that can be used in a multitude of industrial use

---

[*] e-mail: natalie.hube@mercedes-benz.com
[†] e-mail: alexander.achberger@mercedes-benz.com
[‡] e-mail: philipp.liepert@mercedes-benz.com
[§] e-mail: jonas.vogelsang@mercedes-benz.com
[¶] e-mail: vidackovic@hdm-stuttgart.de
[‖] e-mail: michael.sedlmair@uni-stuttgart.de

cases. One STRIVE has a string that can be connected to the users' controller, tool or HMD, depending on where they want to feel the haptic feedback. When the users are colliding with a virtual object, STRIVE stops their movement by blocking the string extraction. It can simulate collisions with varying degrees of freedom using multiple STRIVE devices that can be placed in the area of use. Due to its flexible usage, we decided to use STRIVE in our user study. For further Information about strive, please read the paper by Achberger et al. [1].

2.2 Upper Limb Representation in Virtual Reality

Another approach to increase immersion in VR is using a virtual representation of the users body. Research examined different types of avatar representations, such as full body [33, 37] or partial avatar representations [14, 28, 30, 35, 36]. Multiple researchers [7, 26] advocate for integrating upper limb representations for self-representing avatars. Depending on the application, the representations vary in their degree of realism and complexity [38, 40]. As it is not yet clear how those parameters affect the user experience in VR, it is a growing research topic. Full-body avatars are not always necessary for specific situations where realism is less important. Argelaguet et al. [4] observed that the sense of agency is stronger for less realistic hands and the sense of ownership greater for more realistic ones. Other researchers [22, 31] discovered that the appearance influences performance in short time physical tasks.

2.3 Visual-Haptic Correlation

To create an immersive VR experience it is not enough to investigate the different sensory inputs on their own. It is important to identify correlations between them, for example, how visual representations affect haptic feedback and to what degree. Participants who embodied an avatar reported on a stronger illusion of touch than participants with no body [15]. Haptic feedback can be leveraged through visual dominance on the perception of an objects properties [24] and a correlation between haptic information and visual representation can be observed [19, 23, 36]. Interaction that reflects the natural experiences of the real world can increase the feeling of being immersed in a virtual environment, however, the interaction has to be consistent in the stimulation [8, 12, 27].

The joint use of avatars and haptic feedback is a highly interesting research field to us. Being rather new topics, current findings need more confirmation. Studies that focus on the body often only examine the degree of realism or body shape. Most research that develops haptic feedback systems does not consider the self-representation and how it could affect perception. Thus, we investigate different upper limb representations (see Figure 1) and their influence on the perception of haptic feedback.

3 METHODS

Our research goal is to investigate the influence of self-representing upper body limbs used within virtual environments in scenarios from the automotive sector. To us, the interplay between haptics and upper limb visualizations are interesting in different scenarios targeting automotive engineering use-cases and will pose as a leading example in our pilot study. Yet, we see also interesting applicability beyond our example. Further, we want to include a haptic feedback device to measure its influence of the avatar visualization. In order to do so, we present three different scenarios that each participant is confronted with during the user study. Each user will be presented with the same upper limb representation to participate in each scenario. One scenario, that is not implementing physical collision, will be supported by vibrotactile haptic feedback and the other scenarios by the kinesthetic haptic feedback device STRIVE [1]. Below, we describe our prototype and the study setup in more detail.

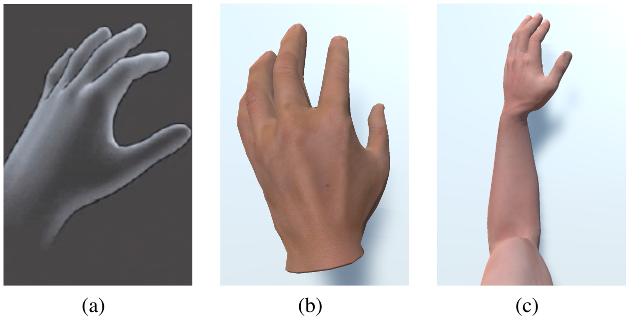
(a) (b) (c)

Figure 1: The upper limb representations used in the study. From left to right: the alienated hand, realistic hand, and the realistic arm.

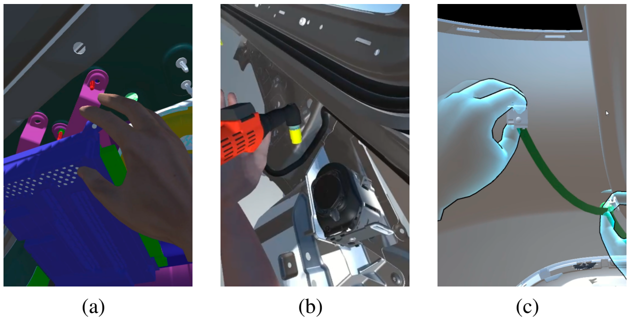
(a) (b) (c)

Figure 2: The three scenarios used in our study. From left to right: quality assurance of data, screw visibility, and construction feasibility.

3.1 Scenario Prototypes

As our target group are engineers within an automotive environment, our focus is on understanding which scenarios require a supportive arm or hand representation and benefit from additional haptic feedback. After a thorough analysis of different scenarios within an automotive company, in which we talked to our target users and their use case related tasks, we chose the most representative scenarios named by our target users. Thus, participants are familiar with the presented tasks. A summary of each scenario can be found in Table 2. *A video figure showing the scenarios and upper limb representations can be found in the supplemental material.*

3.1.1 Quality Assurance of Data (S1)

Here, the main goal is to investigate a simplified CAD-data visualization in an early stage of development. Participants have to analyze a digital snapshot model and detect collisions or wrong positioning (see Fig. 2(a)). Once an error was identified participants points at the given part and describe the collision in detail. To identify all errors the user can either move the model or physically move around in the VR space. We used a vibrotactile haptic feedback provided by VR controllers that is initially applied when the user grabs the model.

3.1.2 Screw Visibility (S2)

In our second scenario, participants test the feasibility of specific screw mountings, which is part of the assembly process (see Fig. 2(b)). Screw mountings are investigated for their visibility and accessibility. Here, the collision of the user, their tools and the 3D model is relevant to identify unreachable screws before building the vehicle in an assembly line. Here, the STRIVE system is used to simulate the collisions between the screwdriver and the 3D model. We used 4 STRIVEs that were attached to the 3D printed screwdriver, and were assembled in the physical environment.

Table 1: An overview of our three selected upper limb representations that we used for our study. In our mixed subject design, each participant is assigned *one* representation type, which they will use throughout the study. Each participant is then tasked with every scenario (S) and with & without haptic feedback (see Table 2).

Representation	Ghost hand (*R1*)	Realistic hand (*R2*)	Realistic arm (R3)
Texture	semi-transparent white	realistic human skin	
Model	hand with wrist		full arm with hand
Results	lowest task load; feeling to be least competent; slowest task completion time on average	average task load index; GEQ results similar to realistic arms, except for competence and positive effect	highest task load, but no indication for a difference between *physical demand* and *performance*, feeling to be most competent; quickest task completion time

Table 2: An overview of our three scenarios and haptic feedback devices we used for scenario in our study. Every participant is tasked with each scenario (S), which is performed with & without haptic feedback.

Scenario	Classic data investigation (*S1*)	Screw visibility (*S2*)	Dynamic construction feasibility (*S3*)
Characteristics	Visualization of CAD-data, data-driven	Assembly investigation, realistic movement interaction	Dynamic construction feasibility, realistic movement interaction
Haptic feedback	with & without haptic feedback		
Type	vibrotactile	kinesthetic	kinesthetic
Tool	VR controller	STRIVE 4DOF, VR Tracker & Manus VR	STRIVE 2DOF & VR Controller

3.1.3 Construction Feasibility (S3)

Flexible parts are investigated during construction feasibility testing. Here, most commonly a wiring harness or tubes are validated within their planned assembly procedure. Participants attach a partial wiring harness in the rear bumper of a vehicle. The goal is to grab digitally provided cables and lay them onto the marked areas. STRIVE is used again to simulate the cable length and collisions between the hands and the 3D model. Here, we used 3 STRIVE devices that were connected to the VR controller and attached on the other controller, the HMD and the user's shoulder.

3.2 Participants

The study consisted of 15 participants (11 male / 4 female) with a mean age of 31.27 years (20 - 56 years). To increase ecological validity, we restricted participation to expert users from within an automotive context, as they are familiar with the presented scenario tasks and know the subtleties that are necessary to complete them. As a discriminating factor, we included tasks that participants know from their day-to-day profession. Our expert users are working with VR on a regular basis. Our participants had a self-estimated experience with VR of 3.33 (*1: very bad - 5: very good*) and 2.07 with haptic feedback tools.

3.3 Variables

Our main independent variable is the upper limb representation. Based on literature, we decided on three representations for our pilot study (see Figure 1), *ghost hand* (R1), *realistic hand* (R2), and *realistic arm* (R3). *Ghost hand* and *realistic hand* use hand models that are cut of beneath the wrist, while *realistic arm* is cut of at the shoulders. However, both realistic representations share a similar texture which resembles the realistic skin of a human. For *ghost hand* we used a semi-transparent texture with a dark outline. The tracking of the hands was accomplished through VR controllers or trackers and for *realistic arm* inverse kinematics was implemented to simulate the movement of the arm with regard to the current hand position. Additionally, we used *haptic feedback* as an independent variable during the study. Participants performed each tasks once with haptic feedback and once with no haptic feedback.

3.4 Tasks & Procedure

In our pilot study, each participant was tasked with three different scenarios and one upper limb representation. First, we gave an introduction to the study and asked participants to fill out a demographic questionnaire. Each scenario was performed in a randomized order to reduce learning effects. Each scenario consisted of tasks in which we applied haptic feedback as well as tasks were we intentionally left the haptic feedback out. Overall, the participants performed 6 tasks. After each task, participants were asked to fill out a questionnaire and have a short break. Each task lasted between 5 - 9 minutes.

3.5 Design & Measures

We used a mixed subject design to compare the upper limb representation and its influence on the perception of haptic feedback in each scenario. Each participant was presented with the same upper limb representation, which were randomly and evenly assigned to the participants. Respectively 5 users were presented with condition *ghost hand*, *realistic hand* and *realistic arm*. While those numbers would be too small for a confirmatory study, we deemed it as sufficient for a starting point of a pilot expert study. The measured data includes task completion times, NASA-TLX [16] and the In-game module of the GEQ (Game Experience Questionnaire) [18]. We also collected subjective feedback and screen-recorded the participants' interaction during the study. Further, we stored transformation data of the hardware and collision states of the virtual representation and the immersive environment. Based on our pilot study design, we have the following guiding questions:

Q1 Does the different upper limb representations influence the experience of haptic feedback?

Q2 Which representation is preferred by our expert users in terms of realism and performance?

3.6 System Description

The prototype was developed using Unity [39]. Our developed environment used the HTC VIVE Pro as the head-mounted display for the immersive environment. As input devices, we used a different setup for each scenarios (see Table 2): (*S1*) used the HTC Vive controller. (*S2*) used a 3D-printed power screwdriver with attached HTC Vive Tracker, Manus VR gloves and the haptic feedback device STRIVE [1] attached to the screwdriver. (*S3*) used the HTC Vive controller with STRIVE attached to the controller.

4 RESULTS

In the following, we present our results including computed means and standard deviations. Effect sizes are shown graphically with

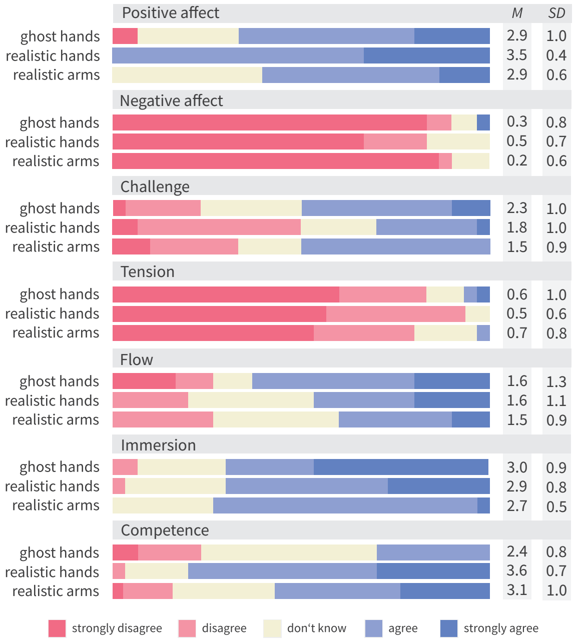

Figure 3: Results from the in-game module of the GEQ for *realistic hand*, *ghost hand* and *realistic arm*. Answers were given using a Likert scale ranging from 0 (*strongly disagree*) - 4 (*strongly agree*).

Figure 4: After each scenario, participants were asked about the used representation and haptic feedback. Results are shown in a stacked bar chart using a Likert scale ranging from 1 (*strongly disagree*) - 5 (*strongly agree*).

plots and 95% confidence intervals.

4.1 Game Experience Questionnaire

The In-game module of the GEQ surveys the game experience on seven components: immersion, flow, competence, positive and negative affect, tension, and challenge [18]. The results (see Figure 3) show that the realistic arm representation seems to have a positive effect and participants seem to feel more competent ($p = 0.0383$). We do not expect an influence on immersion ($p = 0.421$), flow ($p = 0.771$), tension ($p = 0.629$) or challenge ($p = 0.159$), nor a negative effect ($p = 0.402$).

4.2 Task Completion Times

During the study, participants were asked to perform specific tasks. We measured the time used by participants to complete each task. The completion time for tasks with haptic feedback (*Mean* = 69.3s, *SD* = 34.0s, *SE* = 5.1s) was only slightly higher than for the tasks without haptic feedback (*mean* = 64.2s, *SD* = 21.1s, *SE* = 3.1s). Apart from the haptic feedback, we compared task completion times for each upper limb representation: *ghost hand* (*Mean* = 80.5s, *SD* = 49.0s, *SE* = 7.2s), *realistic hand* (*Mean* = 73.1s, *SD* = 43.2s, *SE* = 6.3s), *realistic arm* (*Mean* = 46.5s, *SD* = 28.5s, *SE* = 4.2s). Here, we found that participants using the realistic arm representation completed tasks faster ($p = 0.005$).

4.3 Subjective Feedback

We measured the participants' opinions on specific statements (see Figure 4). Additionally, we analyzed the oral feedback of participants, recorded video material and logged data. Here, we found that three of five participants in the *ghost hand* condition mentioned difficulties predicting collisions with a 3D object over all scenarios.

> *It was hard to tell, if the model was colliding with my [ghost] hands or not.* (P1 & P3)

After rewatching the video footage, we found only participants equipped with the *ghost hand* representation experienced difficulties predicting collisions. While analyzing the video footage together with the logged data, we discovered that participants moved more during the study due to the opaque texture of the upper limb representation and less when using the *ghost hand* representation.

> *I did not think about my virtual [realistic] hands anymore, while performing the task.* (P11)

Additionally, participants who were equipped with a realistic hand or realistic arms emphasized, that after a while they did not notice their self-representation anymore. This indicates that participants were fully immersed in their environment. However, this is not reflected in the results of the GEQ (see Fig. 3) and needs further investigation.

> *While performing the tasks, I totally forgot about my [realistic] arms.* (P4 & P9)

4.4 NASA-TLX

We asked our participants to fill out the NASA-TLX questionnaire after each task, resulting in a total of 45 observations for each item. A two-way ANOVA was performed to analyze the task-load index of the influence of haptic feedback and different limb representations on the perceived feedback statistically. The results revealed no significant interaction between the effects of haptic feedback and upper limb representations ($F(2,84) = 0.49, p = 0.6$). The simple main effects analysis showed that applying haptic feedback did not have a statistically significant effect on the experience of haptic feedback ($p = 0.062$), nor did the representation ($p = 0.093$). Here, we want to note that the study is not adequately powered ($N = 15$, with 5 participants per limb representation), thus, we additionally show confidence intervals [25] (see Fig. 5). The task load index was checked individually for the different upper limb representations and plotted in a scale of 0-100. Although the results did not reveal statistical differences, they still show us a potential bias for a difference between the representation used and the haptic feedback, which we can look into further in future studies.

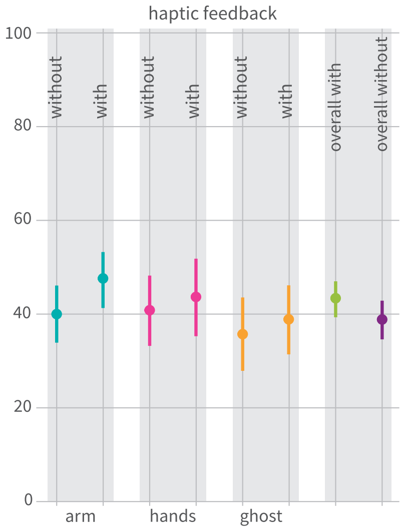

Figure 5: The NASA-TLX measures the perceived workload. The scale is rated within a 100 points rage *(0: very low - 100: very high)*. All ratings are combined to the TLX, with 🟩 and without 🟪 haptic feedback for each upper limb representation. The plot shows the 95% confidence intervals.

5 DISCUSSION

The results of the pilot study indicate various advantages of using *realistic arms* as the upper limb representation together with haptic feedback for self-representing avatars. In Table 1, we give an overview of our study and its results.

5.1 Upper Limb Representation

Based on our study results, we discovered that users seem to prefer using a realistic arm or hand representation. Similar to results from Ferran et al. [4], we found that with an increasing level of realism, participants indicated to have a higher ownership (see Figure 4). With regard to the GEQ, we could not find significant differences between the upper limb representation, just a slight tendency towards the arm representation. Looking at the data we gathered after each task, we think that the indicated measures might be influenced by the given scenario. Yet, participants felt more competent when using the realistic arm compared to the other representation and stated to have a higher positive effect from this representation during the task. Participants using the ghost hand representation felt less competent. A potential reason can be found in the participants oral feedback, as participants mentioned the transparent texture made it harder to estimated collisions and distances between the hand model and a 3D object in all three scenarios . Opposed to Afonso et al. [2], we found that the overall task completion time is likely to be lower for the realistic arm representation. However, due to the small sample size, the variance of results is rather broad, thus, this discovery needs to be further investigated.

5.2 Working on Tasks Using Haptic Feedback

Research suggests that using haptic feedback might decrease the task load during an assignment [41], although this finding is dependent on the use case and haptic feedback device. As we were using a kinesthetic feedback device, we expected a higher task load for using haptic feedback (see Fig. 5) due to the device restricting users' movement during the task. The gathered data supports our claim. However, we did not find a difference between the physical demand and estimated performance between both conditions. Of course, we need to keep in mind the low-powered, pilot study setup when interpreting such results.

When comparing the TLX for the upper limb representation, we found that using the *realistic arm* in combination with haptic feedback received the highest task load. That is due to the opaque texture of the arm representation, as participants were not able to look through their arm and, thus, had to reposition themselves more often to complete the tasks. Looking at the video footage and the logged data, we can confirm this assumption. Participants using the ghost hand, which allowed greater visibility due to the semi-transparent texture, without haptic feedback did not show this type of movement in the footage and resulted in a lower task load index.

According to the participants answers (see Figure 4), the upper limb representation not necessarily prevented or supported participants from doing a specific task. Yet, the realistic arm representation matched the haptic feedback more often (9 of 15 times) compared with the other representation conditions. Additionally, participants stated that the experience of haptic feedback was increased by using the realistic arm representation (11 of 15 times) opposed to the participants using the ghost hand or realistic hand representation, although participants not necessarily performed better.

6 LIMITATIONS

Our work has some limitations that need to be considered when looking at the results. Due to our pilot approach and non-confirmatory setup, our results should be used as an inspiration for future studies as it is not possible to reliably derive causal relationships. Thus, with 15 participants, five per representation condition, generalization might not be fully supported. Additionally, we reduced the task complexity to fit the reduced sample size. Thus, the task participants were performing during the study were simplified. Further, we used a vibrotactile and a kinesthetic haptic feedback system in our user study and plan to include more devices to test whether the observed effects are consistent across various systems. Also, our mixed study design needs to be improved with regard to data collection for the different scenarios. Here, we found that differences might exist between specific scenarios, but to fully support these claims and detect potential interaction effects, we want to further adapt our study setup.

7 CONCLUSION & FUTURE WORK

In this paper, we examined different upper limb representations and their influence on haptic feedback in a pilot user study with 15 participants. Specifically, we tasked participants in three scenarios using one of three different upper limb representations. Additionally, participants performed tasks with and without haptic feedback. We found evidence that participants preferred the realistic arm representation in VR and might perform tasks quicker with it when using haptic feedback. We believe that using a realistic arm as a self-representation is more beneficial than using only a hand or semi-transparent texture, but need to investigate that assumption in the future with more participants.

For future work, we want to include further haptic feedback devices to investigate whether different types of systems vary in their influence on the feeling of ownership of the users' representation. We are also interested in focusing on different scenarios from within the automotive context, as one combination of upper body representation with haptic feedback might be more beneficial than another combination. Overall, we are interested in including full-body avatars in a collaborative multi-user setup.

ACKNOWLEDGMENTS

Funded by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy - EXC 2075 – 390740016.

REFERENCES

[1] A. Achberger, F. Aust, D. Pohlandt, K. Vidackovic, and M. Sedlmair. Strive: String-based force feedback for automotive engineering. In *Proc. of ACM Conf. on User Interface Software and Technology (UIST)*, pp. 841–853, 2021.

[2] L. Afonso, P. Dias, C. Ferreira, and B. S. Santos. Effect of hand-avatar in a selection task using a tablet as input device in an immersive virtual environment. In *Proc. IEEE Conf. on Virtual Reality and 3D User Interfaces (VR)*, pp. 247–248. IEEE, 2017.

[3] Anonym. Anonym. In *Anonym.* Anonym.

[4] F. Argelaguet, L. Hoyet, M. Trico, and A. Lécuyer. The role of interaction in virtual embodiment: Effects of the virtual hand representation. In *Proc. IEEE Conf. on Virtual Reality and 3D User Interfaces (VR)*, pp. 3–10. IEEE, 2016.

[5] Autodesk, Inc. VRED. `https://www.autodesk.de/products/vred/overview`, 2019. last accessed on 2021-07-25.

[6] L. P. Berg and J. M. Vance. Industry use of virtual reality in product design and manufacturing: a survey. *Virtual reality*, 21(1):1–17, 2017.

[7] S. Bovet, H. G. Debarba, B. Herbelin, E. Molla, and R. Boulic. The critical role of self-contact for embodiment in virtual reality. vol. 24, pp. 1428–1436, 2018. doi: 10.1109/TVCG.2018.2794658

[8] E. Burns, S. Razzaque, A. T. Panter, M. C. Whitton, M. R. McCallus, and F. P. Brooks. The hand is slower than the eye: A quantitative exploration of visual dominance over proprioception. In *Proc. IEEE Conf. on Virtual Reality and 3D User Interfaces (VR)*, pp. 3–10. IEEE, 2005.

[9] S. Eroglu, F. Stefan, A. Chevalier, D. Roettger, D. Zielasko, T. W. Kuhlen, and B. Weyers. Design and evaluation of a free-hand vr-based authoring environment for automated vehicle testing. In *Proc. IEEE Conf. on Virtual Reality and 3D User Interfaces (VR)*, pp. 1–10. IEEE, 2021.

[10] ESI Group. IC.IDO. `https://www.esi-group.com/products/virtual-reality`, 2019. last accessed on 2021-07-25.

[11] C. Fang, Y. Zhang, M. Dworman, and C. Harrison. Wireality: Enabling complex tangible geometries in virtual reality with worn multi-string haptics. In *Proc. ACM Conf. Human Factors in Computing Systems (CHI)*, pp. 1–10, 2020.

[12] D. Gall and M. E. Latoschik. The effect of haptic prediction accuracy on presence. In *Proc. IEEE Conf. on Virtual Reality and 3D User Interfaces (VR)*, pp. 73–80. IEEE, 2018.

[13] P. Garrec, J.-P. Friconneau, and F. Louveau. Virtuose 6d: A new force-control master arm using innovative ball-screw actuators. In *International Symposium on Robotics*, 2004.

[14] J. K. Gibbs, M. Gillies, and X. Pan. A comparison of the effects of haptic and visual feedback on presence in virtual reality. p. 102717. Elsevier, 2021.

[15] M. Gonzalez-Franco and C. C. Berger. Avatar embodiment enhances haptic confidence on the out-of-body touch illusion. *IEEE Transactions on Haptics*, 12(3):319–326, 2019. doi: 10.1109/TOH.2019.2925038

[16] S. G. Hart and L. E. Staveland. Development of nasa-tlx (task load index): Results of empirical and theoretical research. In *Advances in psychology*, vol. 52, pp. 139–183. Elsevier, 1988.

[17] M. Hermann, T. Pentek, and B. Otto. Design principles for industrie 4.0 scenarios. In *Hawaii International Conference on System Sciences (HICSS)*, pp. 3928–3937, 2016.

[18] W. IJsselsteijn, Y. de Kort, and K. Poels. *The Game Experience Questionnaire*. Technische Universiteit Eindhoven, 2013.

[19] D. A. G. Jáuregui, F. Argelaguet, A.-H. Olivier, M. Marchal, F. Multon, and A. Lecuyer. Toward" pseudo-haptic avatars": Modifying the visual animation of self-avatar can simulate the perception of weight lifting. vol. 20, pp. 654–661. IEEE, 2014.

[20] S. Je, M. J. Kim, W. Lee, B. Lee, X.-D. Yang, P. Lopes, and A. Bianchi. Aero-plane: A handheld force-feedback device that renders weight motion illusion on a virtual 2d plane. In *Proc. of ACM Conf. on User Interface Software and Technology (UIST)*, pp. 763–775, 2019.

[21] Y. Kishishita, A. Vega Ramirez, S. Das, C. Thakur, Y. Yanase, and Y. Kurita. Muscleblazer: a wearable laser tag module powered by pgm-induced force-feedback. In *International Symposium on Amplifying Capabilities and Competing in Mixed Realities*, pp. 1–6, 07 2018.

[22] M. Kocur, M. Kloss, V. Schwind, C. Wolff, and N. Henze. Flexing muscles in virtual reality: Effects of avatars' muscular appearance on physical performance. In *Proc. ACM Conf. Human Factors in Computing Systems (CHI)*, CHI PLAY '20, p. 193–205. ACMs, New York, NY, USA, 2020.

[23] M. Kuschel, F. Freyberger, M. Buss, and B. Färber. A presence measure for virtual reality and telepresence based on multimodal conflicts. In *International Workshop on Presence (PRESENCE)*. Citeseer, 2007.

[24] A. Lécuyer. Simulating haptic feedback using vision: A survey of research and applications of pseudo-haptic feedback. vol. 18, pp. 39–53. MIT Press, 2009.

[25] E. C. Lee, A. L. Whitehead, R. M. Jacques, and S. A. Julious. The statistical interpretation of pilot trials: should significance thresholds be reconsidered? vol. 14, pp. 41 – 41, 2014.

[26] J.-L. Lugrin, M. Ertl, P. Krop, R. Klüpfel, S. Stierstorfer, B. Weisz, M. Rück, J. Schmitt, N. Schmidt, and M. E. Latoschik. Any "body" there? avatar visibility effects in a virtual reality game. In *Proc. IEEE Conf. on Virtual Reality and 3D User Interfaces (VR)*, pp. 17–24, 2018.

[27] N. Magnenat-Thalmann and U. Bonanni. Haptics in virtual reality and multimedia. vol. 13, pp. 6–11. IEEE, 2006.

[28] J. Martinez, D. Griffiths, V. Biscione, O. Georgiou, and T. Carter. Touchless haptic feedback for supernatural vr experiences. In *Proc. IEEE Conf. on Virtual Reality and 3D User Interfaces (VR)*, pp. 629–630. IEEE, 2018.

[29] M. Moehring, A. Gloystein, and R. Doerner. Issues with virtual space perception within reaching distance: Mitigating adverse effects on applications using hmds in the automotive industry. In *Proc. IEEE Conf. on Virtual Reality and 3D User Interfaces (VR)*, pp. 223–226, 2009. doi: 10.1109/VR.2009.4811027

[30] S. Mulatto, A. Formaglio, M. Malvezzi, and D. Prattichizzo. Using postural synergies to animate a low-dimensional hand avatar in haptic simulation. vol. 6, pp. 106–116, 2013. doi: 10.1109/TOH.2012.13

[31] O. Ossmy and R. Mukamel. Short term motor-skill acquisition improves with size of self-controlled virtual hands. vol. 12, p. e0168520. Public Library of Science San Francisco, CA USA, 2017.

[32] J. Perret and L. Dominjon. The inca 6d: a commercial stringed haptic system suitable for industrial applications. In *Joint Virtual Reality Conference, Springer Tracts in Advanced Robotics*, 2009.

[33] G. Richard, T. Pietrzak, F. Argelaguet, A. Lécuyer, and G. Casiez. Studying the role of haptic feedback on virtual embodiment in a drawing task. vol. 1, p. 28. Frontiers, 2021.

[34] M. Rietzler, F. Geiselhart, J. Frommel, and E. Rukzio. *Conveying the Perception of Kinesthetic Feedback in Virtual Reality Using State-of-the-Art Hardware*, p. 1–13. Association for Computing Machinery, New York, NY, USA, 2018.

[35] V. Schwind, J. Leusmann, and N. Henze. Understanding visual-haptic integration of avatar hands using a fitts' law task in virtual reality. In *Proceedings of Mensch Und Computer (MuC)*, p. 211–222. Association for Computing Machinery, New York, NY, USA, 2019.

[36] V. Schwind, L. Lin, M. Di Luca, S. Jörg, and J. Hillis. Touch with foreign hands: The effect of virtual hand appearance on visual-haptic integration. In *Proceedings of the 15th ACM Symposium on Applied Perception*, pp. 1–8, 2018.

[37] B. Spanlang, J.-M. Normand, E. Giannopoulos, and M. Slater. A first person avatar system with haptic feedback. In *Proc. ACM Symp. on Virtual Reality Software and Technology (VRST)*, p. 47–50. Association for Computing Machinery, New York, NY, USA, 2010.

[38] Spatial Systems Inc. HoloLens Spatial. `https://spatial.io/`, 2020. last accessed on 2020-07-25.

[39] Unity Technologies. Unity 3D. `https://unity.com/`, 2022. last accessed on 2022-01-04.

[40] VRChat Inc. VR Chat. `https://vrchat.com/`, 2019. last accessed on 2020-07-25.

[41] J. G. Wildenbeest, D. A. Abbink, C. J. Heemskerk, F. C. Van Der Helm, and H. Boessenkool. The impact of haptic feedback quality on the performance of teleoperated assembly tasks. vol. 6, pp. 242–252. IEEE, 2012.

[42] P. Zimmermann. Virtual reality aided design. a survey of the use of vr in automotive industry. In *Product Engineering*, pp. 277–296. Springer, 2008.