# Experience Haptics *Seamlessly* Across Virtual and Real Worlds

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## ABSTRACT

Haptic feedback has been an important contributor to enabling more immersive and dexterous experiences in virtual worlds. Yet achieving realistic haptic feedback is not trivial. Take tactile feedback for example, our skin can sense complex sensations (e.g., vibration, pressure, temperature) with high sensitivity and wide range. Attempting to render all these complex sensations has led to very realistic haptic devices, but, these are necessarily cumbersome and obstructive (e.g., haptic gloves that need to cover the whole hand with several actuators). While this might be fine in VR where users only interact with virtual objects, this is completely at odds with every other interface paradigm, such as Augmented Reality or Mixed Reality, in which users not only interact with virtual objects but *also* with their surroundings (e.g., tool manipulation). We argue that to make haptic devices available to use beyond VR, we must design for the *integration* between the haptic device and the real world. To this end, we demonstrate new approaches to engineering haptics devices that allow users to feel haptics from the real world and augment haptics to the real world. With this shift in haptics, we believe that in the future, users will be able to enjoy the benefits of haptics without needing to choose between either only a virtual world with haptics or a real world without—instead, experiencing haptics seamlessly *across* both real and virtual worlds.

**Keywords**: Haptics, VR, AR, MR, Spatial Computing

## 1 INTRODUCTION

Haptic feedback has been an important factor in more immersive and more dexterous experiences [18, 27]. In fact, advances in haptic devices have historically gone hand in hand with advances in most interface paradigms. For instance, every time that VR advanced, haptics was there to provide more immersive virtual interactions [4, 8, 16, 26]. With haptic devices, users in VR are able to feel forces and touches arising from virtual worlds, be it clicking a button [12] or feeling the texture of an object [34]. These devices have proved useful in many settings, e.g., physical skill training [18], remote operation [30], and entertainment [26]. With the trend of current mobile computing development, e.g., Augmented Reality, wearable tactile devices have the potential to go beyond VR and open new applications, e.g., always-available sensory experiences that feel realistic and personalized.

However, haptic devices are typically large and cumbersome, which limits their use outside of VR contexts. For example, haptic gloves can provide realistic touch feedback but also completely cover the user's hands and fingerpads [25]—while this might be fine in VR where users only interact with virtual objects, this is completely at odds with every other interface paradigm, such as Augmented Reality/Mixed Reality, in which users not only interact with virtual objects but also with their surroundings (e.g., tool manipulation, etc.). We argue that the reason behind this is that most haptic interfaces were designed with the main goal of optimizing the rendering of virtual sensations [21, 25]. These realistic haptic sensations are typically realized by integrating many actuators that offer various haptic modalities (vibration, pressure, temperature, etc.). Unfortunately, as more actuators are added to the device to increase realism, the device becomes larger, heavier, and, more importantly, *blocks more of the user's skin*. Haptics have largely been explored in isolation from considerations of user's physical interactions with surrounding objects.

In this paper, we argue that in order to make haptic devices useful outside of VR, we must design haptics that works across the virtual and the real world. We first show some examples that highlight the problem of traditional approaches, in which physical objects are involved. Then we introduce our approaches along with prototypes that we had developed (some published) to design haptics that considers both the virtual and the real world. We discuss potential new applications and open challenges following this new direction. We hope in the future, users do not have to choose between either only a virtual world with haptics or a real world without—instead, can experience haptics seamlessly *across* both real and virtual worlds.

## 2 PROBLEMS WITH TRADITIONAL HAPTIC DEVICES

The advancement of immersive headsets opens up new usage scenarios such as Augmented Reality; yet, traditional haptic devices conflict with these. Not only their current designs were not for them, the more advanced these haptic devices are, the more conflicts. Here, we illustrate the problem with the traditional haptics approach with some examples of immersive experiences:

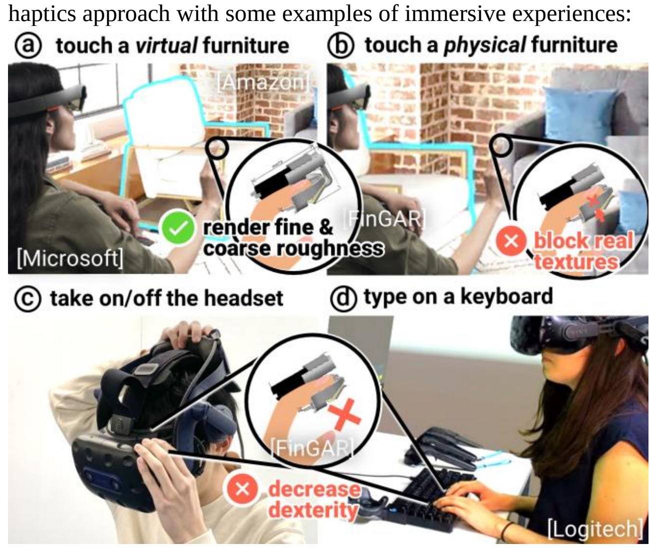


Figure 1: **Haptic devices limit users when they transition from virtual-to-physical interactions**: (b) haptic devices prevent the user from interacting with physical objects (e.g., furniture), and (c, d) degrade the user's dexterity while operating other devices (e.g., headsets or keyboards).

**Conflict with physical objects.** We illustrate the limitations of current haptic approaches when used in conjunction with AR applications, which typically involve interactions with both virtual and physical objects. One canonical example is an AR application where the user arranges virtual pieces of furniture in their own living spaces, exploring how they might fit best before purchasing the physical item [1, 24]. While researchers and industry have proposed adding haptics to these experiences, so that users can also feel the texture, weight, and shape of the virtual furniture [13, 27, 33], as depicted in Figure 1 (a), these haptic devices cover the users' fingerpads with their actuators and prevent users from touching the physical surroundings, e.g., the user cannot compare the virtual texture on a furniture to the physical one, as depicted in Figure 1 (b). Besides this example, almost all AR applications involving touch will suffer from this limitation. The user either wears the haptic device to feel the virtual texture, or they would have to take off the device to feel the physical texture. While visually the virtual and the physical blend together seamlessly, the haptics does not.

**Conflict with operating other devices.** This problem is particularly interesting in that it is *not* typically discussed in research: the addition of haptic devices is well-known to add value to interactions (e.g., especially in VR), but it is rarely discussed how these devices also remove value as they dimmish the user's abilities to interact with other devices. We depict this in the example of two interactions in VR. First, Figure 1 (c) illustrates a user struggling to get into a VR headset while wearing a haptic device on their fingerpads—a situation that readers who tried VR + haptics demonstrations at a conference are likely to be familiar with. Second, Figure 1 (d) shows that while haptic devices excel at providing haptic sensations for virtual content, they can interfere with other devices or tools, e.g., a physical keyboard for typing in VR [14].

These examples are just a starting point to illustrate the fundamental problem of optimizing haptics *only* for the virtual world. It creates obstacles for haptic devices to move on beyond VR usage. Instead, we argue that we need to design haptics for *both* the virtual and real world to achieve seamless experiences.

## 3 HAPTICS THAT WORKS SEAMLESSLY ACROSS BOTH THE VIRTUAL WORLD AND THE REAL WORLD

To design haptic devices that involve the real world, we emphasize that devices should enable seamless transitions between various interaction paradigms, including VR, AR, and reality in real-virtual continuum [20]. Figure 2 depicts a simplified diagram of how a simple touch interaction looks like when interacting with both virtual and real objects: (1) haptics from the virtual object, (2) haptics from the real object; and (3) haptics from the augmented real objects.

While many have explored creating haptics for each type of interaction, we argue that it is the *transitions* that are often ignored and have led to the aforementioned problem. As such, we highlight the need to create *seamless transitions*:

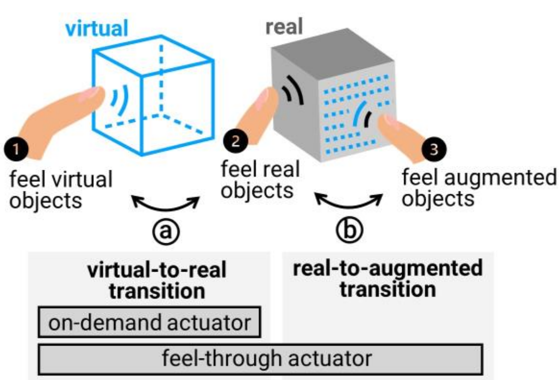


Figure 2: We highlight the importance of seamless transitions from (a) virtual-to-real, and (b) real-to-augmented interactions.

**(a) Seamless transition from virtual to the real haptics.** This transition has proven difficult because it requires the haptic device to stimulate the user's fingerpad if they touch a virtual object, while letting the fingerpad be free when they touch real objects. While current haptic devices excel at rendering the sensation of the virtual object—depicted as (1) in Figure 2—they cannot let the user feel real objects without taking off the devices [25]. A seamless transition is missing from virtual-to-real, as depicted in Figure 2 (a).

**(b) Seamless transition from real to augmented haptics.** This transition is even harder as it requires the haptic device to be able to let the user, *simultaneously*, feel the haptics inherent to a real object and any haptics rendered atop the real object's existing feel (often referred to as an *augmentation*). While past research for haptic augmentation has shown attaching actuators onto other parts of the hand [19], these can sacrifice the realism of such augmentation. An improved and seamless transition from real-to-augmented is still missing, as depicted in Figure 2 (b).

We will demonstrate one possible approach to support transition (a) with on-demand actuators and another possible approach to cover both transition (a) and (b) with feel-through actuators.

## 4 SEAMLESS HAPTIC TRANSITION A: ON-DEMAND ACTUATOR

Ideally, with nothing covering up the fingerpads, users can enjoy the full haptic perception when interacting with the real world. We propose an approach that can leave the fingerpads free for real-world objects by designing haptic actuators to only come in contact when needed, i.e., *on-demand*, as depicted in Figure 3.


Figure 3: This foldable actuator mounted on the fingernail keeps the fingerpad free as default, and extends itself to press on the fingerpad to render the sense of touch.

We demonstrated this approach through a prototype, Touch&Fold [29], which is a nail-mounted foldable haptic device that provides tactile feedback to AR/MR environments by pressing against the user's fingerpad when a user touches a virtual object. The device quickly tucks away (92 ms) when the user interacts with real-world objects. Its design allows it to fold back on top of the user's nail when not in use, keeping the user's fingerpad free to, for instance, manipulate handheld tools and other objects while in MR (an example in Figure 4). Our foldable end-effector also features a linear resonant actuator, allowing it to render not only touch contacts (i.e., pressure) but also textures (i.e., vibrations).

In our user studies, we found that participants perceived our device to be more realistic than a previous haptic device that also leaves the fingerpad free (i.e., fingernail vibration [2]). We believe this was due to the fact that our device can render haptics on the part that made contact with the virtual objects, i.e., the fingerpad. We also found that our device allowed participants to use the same finger to manipulate handheld tools & small objects, and even feel textures and liquids, without much hindrance to their dexterity, while feeling haptic feedback when touching AR/MR interfaces.

By folding away, more bulky actuators can be integrated onto the device. This approach can be extended beyond pressure feedback to include other sensations, such as temperature (e.g., via Peltier elements).

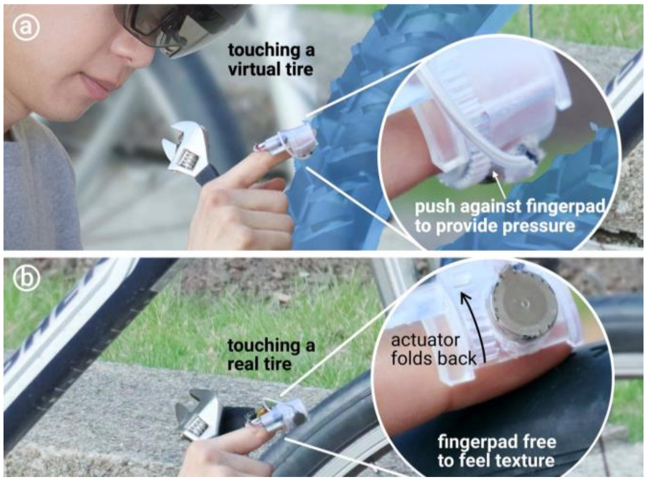


Figure 4: This approach enables a user in Mixed Reality to feel the texture of a virtual tire; yet they are also able to feel the texture of a real tire when they touch it, because the device folds back and reveals the whole fingerpad.

On-demand actuators provide a swift transition of a device that is suitable for the virtual world to that for the real world, and vice versa. However, it cannot support the haptic transition to augmentation of real objects. We will demonstrate another approach that can cover both transition (a) and (b) in Figure 2.

## 5 Seamless Haptic Transition A & B: Feel-Through

To achieve a smooth transition from the real to the augmented, one can design haptic actuators so thin that it is mechanically imperceptible and allow users to still feel the sensations from the real world through the devices, i.e., *feel-through*. Recently, many researchers have turned to electrode-films with electrotactile stimulation [32]. Although this allows users to still feel some sensations through the devices when touching physical objects (e.g., compliance or some macro features), studies have shown that our haptic perception of texture can be impaired even if covered with films of a few microns (less accurate discrimination of roughness [23]). Because tactile information is important for grip control (controlling grasping force so that not too little/too much force is used), grasping efficiency is also affected when the fingerpads are covered with films [5].

We proposed a simple yet effective approach to improve the haptic perception in thin film actuators: adding small holes to films can allow the skin to direct contact with any physical objects [28], as depicted in Figure 5.


Figure 5: Adding holes to existing thin-film actuators can reveal fingerpad ridges, and thus improve haptic perception for physical objects.

Our preliminary results show that adding holes: (1) improved perception of tactile features (grating orientation discrimination); and (2) improved force control in grasping tasks. This is potentially due to fingerpad ridges that are revealed through the holes allowing mechanoreceptors to receive more accurate tactile information. We observed participants in interactive experiences and found that holes can preserve dexterity with physical tasks while still benefiting from haptic feedback for virtual interfaces and haptic augmentation for real objects, as depicted in Figure 6.


Figure 6: This approach enables dexterous activities in MR, where the user can feel haptic feedback for virtual interfaces (e.g., a button), can have better grip control when grasping physical objects (e.g., a screwdriver), and can experience haptic augmentation (e.g., vibration of a passive toy truck).

## 6 Potential New Applications of Haptics Beyond VR

By developing haptic devices for *seamless* transitions between the virtual and the real world, we can envision new applications that go beyond just VR haptics. These can range from enhancing productivity, immersive experiences, or even improving physical skill acquisition for real-world tasks.

**Boost task performance across virtual & real.** While bare-hand interaction provides the natural & versatile input for AR, it is often very difficult to perform dexterous manipulation, from a simple button-pressing to typing, without haptic feedback. Studies have shown that vibration on fingers can improve typing in mid-air [10]. By enabling this haptic transition, a user can seamlessly move between using a physical keyboard to a virtual keyboard.

While the current performance of virtual keyboards is still behind typing with a physical keyboard (possibly due to the fact that a physical keyboard offers more tactile information other than just vibration), we can expect that adding more haptic modalities will allow users to type on a virtual keyboard as fast as if they were typing on a physical keyboard. This usability improvement can also be expected to other control interfaces, such as sliders & knobs (e.g., as used in music production, machinery, home appliances, etc.), and may also improve other virtual interfaces that do not even have physical counterparts (e.g., gestures).

**Seamless haptics for immersive content from the virtual & real world.** With haptic devices that work across the virtual and the real world, we can envision users feeling realistic haptic rendered seamlessly along with physical objects in their surroundings. For example, in AR, the user can not only try on virtual clothes, *but also* compare the texture of virtual fabrics with the texture of their own clothing by touch. As for designers, they can design virtual products in-situ, preview objects before they are made, and feel how it works alongside other physical objects (e.g., feeling the material of a phone case on a real phone). Many more seamless sensations are possible. For instance, in an AR meeting, one can shake hands with the remote person shown in their headset, and feel the warmth of their hands, but also shake hands with a person nearby, as the haptic devices will not be in the way—this could potentially facilitate remote and in-person collaboration [22].

**In-situ haptic learning for physical skills.** Training with haptic feedback is typically utilized only in specific sites (e.g., specialized labs, training centers) because devices are cumbersome and only are designed for virtual interactions [3, 9]. With new wearable haptic devices that are designed to work with physical objects, they can offer direct guidance on many physical tasks in situ. For example, when holding a badminton racket, a haptic device on the player's hand can guide the player which area of the hand to contact the handle (with high-resolution rendering across the fingers and the palm) and how much pressure they should apply (e.g., excessive force can lead to injuries). For sewing, haptic guidance on the fingerpads can be used to directly instruct more precise placement when holding a needle in a real scenario rather than a simulation. We envision haptic devices can play a larger role in skill training if they are designed to preserve the user's dexterity and fit in the environments where the real tasks take place.

## 7 Conclusion & Outlook

In this paper, we propose a new direction for designing haptic devices, not only for the virtual sensations, but also for the sensations from the real world, achieving seamless experiences between the virtual and the real. While we have shown two approaches to realize the first steps of this vision, much is still left to be explored. We project outlook to future research:

**Integration of more haptic modalities, virtual & real.** While we've shown prototypes with limited modalities (e.g., electrotactile or pressure), natural haptic sensations consist of many other modalities (e.g., skin-stretch of multiple degrees-of-freedom [27], thermal sensation [26], chemical sensation [7, 17]). As such, a critical challenge ahead is how to increase the number of available modalities while still maintaining the device small and unencumbering to the user's dexterity.

**Balancing useful haptics for virtual & real world.** Tradeoffs in terms of haptic rendering (e.g., resolution) and haptic perception (i.e., acuity for the real world) may be required because of technical limitations. For example, rendering information like characters or letters may require virtual haptics of a higher resolution [15], which could lead to more obstruction of the real world (i.e., more skin covered). It might be worth investigating the balance between virtual and real-world haptics in terms of different interactive domains (e.g., realistic rendering vs. symbolic information).

**Seamless haptics all day long.** With new interfaces being designed to minimize interference with everyday tasks (e.g., see-through AR or smartwatches allow users to carry on tasks like eating or running), we see an increase in device use time. Similarly, we can expect that if haptic devices can seamlessly switch from virtual to real world, these interfaces will be used for longer periods. However, to design a device for a whole day's usage requires more than to make sure that haptics feels natural. Factors such as power consumption, latency, robustness, comfort, and the user's the willing to wear it, should be considered [6].

**Seamless haptic transitions beyond the fingerpad.** While we focused on haptic devices for fingerpads as these areas are involved with most dexterous manual tasks [25], one can envision exploring our approaches in other body areas. In fact, we are already observing some emergent examples that explore how haptic devices for feet [31] or lips [11] allow users to still feel sensations from the real world on those body areas.

**Conclusion.** It will be challenging to design haptics across the virtual and real world; yet we believe it is a critical direction and this will allow haptics to play many more roles beyond VR—in fact, this might be a key factor in inspiring users to experience haptics *anywhere, anytime*.

## References


[1] Ahlers, K.H., Kramer, A., Breen, D.E., Chevalier, P.-Y., Crampton, C., Rose, E., Tuceryan, M., Whitaker, R.T. and Greer, D. 1995. Distributed Augmented Reality for Collaborative Design Applications. *Computer Graphics Forum*. 14, 3 (1995), 3–14. https://doi.org/10.1111/j.1467-8659.1995.cgf143_0003.x.

[2] Ando, H., Kusachi, E. and Watanabe, J. 2007. Nail-mounted Tactile Display for Boundary/Texture Augmentation. *Proceedings of the International Conference on Advances in Computer Entertainment Technology* (New York, NY, USA, 2007), 292–293. https://doi.org/10.1145/1255047.1255131.

[3] Bae, J.H., Ploch, C.J., Lin, M.A., Daniel, B.L. and Cutkosky, M.R. 2016. Display of needle tip contact forces for steering guidance. *2016 IEEE Haptics Symposium (HAPTICS)* (Apr. 2016), 332–337. https://doi.org/10.1109/HAPTICS.2016.7463199.

[4] Benko, H., Holz, C., Sinclair, M. and Ofek, E. 2016. NormalTouch and TextureTouch: High-fidelity 3D Haptic Shape Rendering on Handheld Virtual Reality Controllers. *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (New York, NY, USA, 2016), 717–728. https://doi.org/10.1145/2984511.2984526.

[5] Bilaloglu, S., Lu, Y., Geller, D., Rizzo, J.R., Aluru, V., Gardner, E.P. and Raghavan, P. 2016. Effect of blocking tactile information from the fingertips on adaptation and execution of grip forces to friction at the grasping surface. *Journal of Neurophysiology*. 115, 3 (Mar. 2016), 1122–1131. https://doi.org/10.1152/jn.00639.2015.

[6] Blum, J.R., Fortin, P.E., Al Taha, F., Alirezaee, P., Demers, M., Weill-Duflos, A. and Cooperstock, J.R. 2019. Getting Your Hands Dirty Outside the Lab: A Practical Primer for Conducting Wearable Vibrotactile Haptics Research. *IEEE Transactions on Haptics*. 12, 3 (Jul. 2019), 232–246. https://doi.org/10.1109/TOH.2019.2930608.

[7] Brooks, J., Nagels, S. and Lopes, P. 2020. Trigeminal-based Temperature Illusions. *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, Apr. 2020), 1–12. https://doi.org/10.1145/3313831.3376806.

[8] Choi, I., Culbertson, H., Miller, M.R., Olwal, A. and Follmer, S. 2017. Grabity: A Wearable Haptic Interface for Simulating Weight and Grasping in Virtual Reality. *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology* (New York, NY, USA, 2017), 119–130. https://doi.org/10.1145/3126594.3126599.

[9] Gonzalez-Badillo, G., Medellin-Castillo, H.I. and Lim, T. 2013. Development of a Haptic Virtual Reality System for Assembly Planning and Evaluation. *Procedia Technology*. 7, (Jan. 2013), 265–272. https://doi.org/10.1016/j.protcy.2013.04.033.

[10] Gupta, A., Samad, M., Kin, K., Kristensson, P.O. and Benko, H. 2020. Investigating Remote Tactile Feedback for Mid-Air Text-Entry in Virtual Reality. *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)* (Nov. 2020), 350–360. https://doi.org/10.1109/ISMAR50242.2020.00062.

[11] Jingu, A., Tanaka, Y. and Lopes, P. 2023. LipIO: Enabling Lips as both Input and Output Surface. *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, Apr. 2023), 1–14. https://doi.org/10.1145/3544548.3580775.

[12] Kim, H., Kim, M. and Lee, W. 2016. HapThimble: A Wearable Haptic Device Towards Usable Virtual Touch Screen. *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2016), 3694–3705. https://doi.org/10.1145/2858036.2858196.

[13] Kim, H., Yi, H., Lee, H. and Lee, W. 2018. HapCube: A Wearable Tactile Device to Provide Tangential and Normal Pseudo-Force Feedback on a Fingertip. *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC Canada, Apr. 2018), 1–13. https://doi.org/10.1145/3173574.3174075.

[14] Knierim, P., Schwind, V., Feit, A.M., Nieuwenhuizen, F. and Henze, N. 2018. Physical Keyboards in Virtual Reality: Analysis of Typing Performance and Effects of Avatar Hands. *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, Apr. 2018), 1–9. https://doi.org/10.1145/3173574.3173919.

[15] Lin, W., Zhang, D., Lee, W.W., Li, X., Hong, Y., Pan, Q., Zhang, R., Peng, G., Tan, H.Z., Zhang, Z., Wei, L. and Yang, Z. 2022. Super-resolution wearable electrotactile rendering system. *Science Advances*. 8, 36 (Sep. 2022), eabp8738. https://doi.org/10.1126/sciadv.abp8738.

[16] Lopes, P., Ion, A. and Baudisch, P. 2015. Impacto: Simulating Physical Impact by Combining Tactile Stimulation with Electrical Muscle Stimulation. *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology* (New York, NY, USA, 2015), 11–19. https://doi.org/10.1145/2807442.2807443.

[17] Lu, J., Liu, Z., Brooks, J. and Lopes, P. 2021. Chemical Haptics: Rendering Haptic Sensations via Topical Stimulants. *The 34th Annual ACM Symposium on User Interface Software and Technology* (New York, NY, USA, Oct. 2021), 239–257. https://doi.org/10.1145/3472749.3474747.

[18] Machaca, S., Cao, E., Chi, A., Adrales, G., Kuchenbecker, K.J. and Brown, J.D. 2022. Wrist-Squeezing Force Feedback Improves Accuracy and Speed in Robotic Surgery Training. *2022 9th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob)* (Seoul, Korea, Republic of, Aug. 2022), 1–8. https://doi.org/10.1109/BioRob52689.2022.9925306.

[19] Maisto, M., Pacchierotti, C., Chinello, F., Salvietti, G., De Luca, A. and Prattichizzo, D. 2017. Evaluation of Wearable Haptic Systems for the Fingers in Augmented Reality Applications. *IEEE Transactions on Haptics*. 10, 4 (Oct. 2017), 511–522. https://doi.org/10.1109/TOH.2017.2691328.

[20] Milgram, P., Takemura, H., Utsumi, A. and Kishino, F. 1995. Augmented reality: a class of displays on the reality-virtuality continuum. *Telemanipulator and Telepresence Technologies* (Dec. 1995), 282–292. https://doi.org/10.1117/12.197321.

[21] Muender, T., Bonfert, M., Reinschluessel, A.V., Malaka, R. and Döring, T. 2022. Haptic Fidelity Framework: Defining the Factors of Realistic Haptic Feedback for Virtual Reality. *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, Apr. 2022), 1–17. https://doi.org/10.1145/3491102.3501953.

[22] Nakanishi, H., Tanaka, K. and Wada, Y. 2014. Remote handshaking: touch enhances video-mediated social telepresence. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (New York, NY, USA, Apr. 2014), 2143–2152. https://doi.org/10.1145/2556288.2557169.

[23] Nittala, A.S., Kruttwig, K., Lee, J., Bennewitz, R., Arzt, E. and Steimle, J. 2019. Like A Second Skin: Understanding How Epidermal Devices Affect Human Tactile Perception. *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2019), 380:1-380:16. https://doi.org/10.1145/3290605.3300610.

[24] Ozturkcan, S. 2021. Service innovation: Using augmented reality in the IKEA Place app. *Journal of Information Technology Teaching Cases*. 11, 1 (May 2021), 8–13. https://doi.org/10.1177/2043886920947110.

[25] Pacchierotti, C., Sinclair, S., Solazzi, M., Frisoli, A., Hayward, V. and Prattichizzo, D. 2017. Wearable Haptic Systems for the Fingertip and the Hand: Taxonomy, Review, and Perspectives. *IEEE Transactions on Haptics*. 10, 4 (Oct. 2017), 580–600. https://doi.org/10.1109/TOH.2017.2689006.

[26] Peiris, R.L., Peng, W., Chen, Z., Chan, L. and Minamizawa, K. 2017. ThermoVR: Exploring Integrated Thermal Haptic Feedback with Head Mounted Displays. *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, Summer 2017), 5452–5456. https://doi.org/10.1145/3025453.3025824.

[27] Schorr, S.B. and Okamura, A.M. 2017. Fingertip Tactile Devices for Virtual Object Manipulation and Exploration. *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, Summer 2017), 3115–3119. https://doi.org/10.1145/3025453.3025744.

[28] Teng, S.-Y., Gupta, A. and Lopes, P. 2024. Haptic Permeability: Adding Holes to Tactile Devices Improves Dexterity. *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (2024). https://doi.org/10.1145/3613904.3642156.

[29] Teng, S.-Y., Li, P., Nith, R., Fonseca, J. and Lopes, P. 2021. Touch&Fold: A Foldable Haptic Actuator for Rendering Touch in Mixed Reality. *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, May 2021), 1–14. https://doi.org/10.1145/3411764.3445099.

[30] Tsetserukou, D., Sato, K., Kawakami, N. and Tachi, S. 2009. Teleoperation system with haptic feedback for physical interaction with remote environment. *2009 ICCAS-SICE* (Aug. 2009), 3353–3358.

[31] Ushiyama, K. and Lopes, P. 2023. FeetThrough: Electrotactile Foot Interface that Preserves Real-World Sensations. *The 36th Annual ACM Symposium on User Interface Software and Technology* (2023). https://doi.org/10.1145/3586183.3606808.

[32] Withana, A., Groeger, D. and Steimle, J. 2018. Tacttoo: A Thin and Feel-Through Tattoo for On-Skin Tactile Output. *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (New York, NY, USA, 2018), 365–378. https://doi.org/10.1145/3242587.3242645.

[33] Yem, V. and Kajimoto, H. 2017. Wearable tactile device using mechanical and electrical stimulation for fingertip interaction with virtual world. *2017 IEEE Virtual Reality (VR)* (Mar. 2017), 99–104. https://doi.org/10.1109/VR.2017.7892236.

[34] Yem, V., Okazaki, R. and Kajimoto, H. 2016. FinGAR: combination of electrical and mechanical stimulation for high-fidelity tactile presentation. *ACM SIGGRAPH 2016 Emerging Technologies* (New York, NY, USA, 24 2016), 1–2. https://doi.org/10.1145/2929464.2929474.