ThermalGrasp: Enabling Thermal Feedback even while Grasping and Walking

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Figure 1: (a) We propose a new approach that enables thermal feedback devices to provide realistic temperature sensations while still allowing users to grab or step on real objects—not only can virtual objects display a temperature, but users can also feel and grasp real objects, such as props. Our approach is different from traditional thermal interfaces, in which Peltier devices are applied to the user's hands to render the temperature of virtual objects. Unfortunately, attaching a Peltier element and its cooling unit (fan and heatsink) directly to one's palm prevents users from also grasping real-world objects. Similarly, existing thermal interfaces cannot be applied to feet soles (as one would need to step on the cooling unit). The result is that existing temperature interfaces are restricted mostly to virtual interactions (hands-free, no props). With ThermalGrasp, (b) we explore a flexible thermal mechanism that allows the cooling unit to be moved away from the user's palms or soles—enabling them to grasp and step on objects.

Abstract

Most thermal interfaces attach Peltier elements and their required cooling systems (heatsinks and fans) directly to the palm or sole, preventing users from grasping or walking. To solve this problem, we present ThermalGrasp, an engineering approach for wearable thermal interfaces that enables users to grab and walk on real objects with minimal obstruction. Our approach moves the therma l device and cooling unit to areas not used in grasping or walking (e.g., dorsal hand/foot). We then use thin, compliant materials to conduct heat to/from the palm or sole. Unlike traditional Peltiers with heatsinks, our thin materials enable grasping and walking on real objects while enjoying thermal feedback. Using our approach, a user can, for example, grasp a passive prop (e.g., a stick that acts as a torch in VR), yet feel its thermal state (e.g., hot due to its flame). In our user studies, ThermalGrasp struck a useful balance between thermal and haptic realism. We believe that ThermalGrasp is a first step towards not forcing users to choose between either feeling thermal feedback or being able to engage with grasping/walking in interactive experiences.

Keywords: thermal feedback, haptic feedback, virtual reality, wearables.

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1 Introduction

Haptic feedback improves user experience in virtual reality (VR) and mixed reality (MR) by providing physical sensations that complement the immersive audiovisuals. Haptics research has led to a remarkable range of wearable haptic devices for delivering tactile (e.g., vibration [1], [2], [3], pressure [4], skin stretch [5], [6]) and force feedback (e.g., exoskeletons [7], [8], [9], [10] or electrical muscle stimulation [11], [12], [13]).

More recently, researchers explored stimulating senses beyond forces and tactile cues, such as providing thermal feedback [14], [15]. At the same time, researchers also demonstrated the compelling use of real-world props as proxies for virtual objects and virtual terrains because they provide cheap yet hyper-realistic haptic feedback [16], [17], [18].

Unfortunately, wearable thermal actuators and props are at odds. This is because typical thermal actuators are inherently bulky or fragile; thus, applying wearable thermal actuators to the user's hands or feet prevents users from grasping or stepping on physical objects (e.g., props or terrains). For example, some recent thermal devices create hot and cold sensations by pumping water through flexible tubes worn by the user [19], [20], [21]. While the tubes' flexibility allows them to conform better to the body, this is also their limitation: any kink in the tubing cuts off the liquid flow and halts the thermal sensations, which happens when a tube is compressed, like if gripped or stepped on.

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As such, the most popular approach to wearable thermal feedback is still the *Peltier* element [22]—a thermoelectric material that, when powered, heats up on one side while cooling down on the other. This makes them appealing for wearables because of their simple electrical control and lack of moving parts or fluids. More recently, even emergent flexible Peltier materials have begun development [23] (price is still prohibitive at 100x the cost of a rigid Peltier, and their flexibility is limited to <12 repeated folds or very small angles). Despite the benefits of Peltiers, to sustain *both hot and cold sensations* (especially lasting more than a few seconds, e.g., rendering temperature of objects and terrains), Peltier elements, both rigid and flexible, *require additional cooling from heatsinks and fans* to remove excess heat from the hot side [24]. Without these bulky cooling units, Peltier elements quickly saturate, i.e., heat leaks from the hot side to the cold side—cascading into a positive feedback loop of undesirable heat.

This requirement for cooling units prevents Peltier elements from being applied to body parts that *contact real objects*, such as the user's palms or soles. In fact, interactive systems based on attaching Peltiers and their heatsinks to users' palms and soles will not allow users to *grasp objects nor walk on top of surfaces*.

To tackle this challenge, we introduce *ThermalGrasp*, an engineering approach for wearable thermal interfaces that enables users to grab and walk on real objects with minimal obstruction. To realize this, our approach moves the Peltier and its cooling unit to areas not used in grasping or walking like the top of the foot or back of hand. We then use thin, compliant materials to *conduct* the Peltier's heating or cooling to the palm or sole. Unlike existing approaches, our thin materials enable grasping and walking on real objects while enjoying thermal feedback. For example, Figure 1 depicts a user walking in a VR desert at dusk, feeling *both* the *sand's texture* and the associated (virtual) *decrease in temperature*.

2 Our approach: ThermalGrasp

ThermalGrasp devices consist of three components, depicted in Figure 2: (1) a thermal element (typically a Peltier but others are possible), (2) **a thermally-conductive yet flexible material** (e.g., heat pipes, sheet metal, etc.), and (3) insulation (e.g., foam, plastics, etc.). The thermally-conductive materials contact the surface of the thermal element (in this case, a Peltier element) and channel the heat flow. Thus, when the Peltier element warms up, heat conducts through the conductive material. By wrapping the channel in insulation, we improve the heat transfer efficiency. The user feels heat at the correct location because we expose the target area's skin to the conductor, while insulating all its other surfaces. Similarly, when the Peltier is cooled, heat is conducted away *from* the user, giving the sensation of cooling.

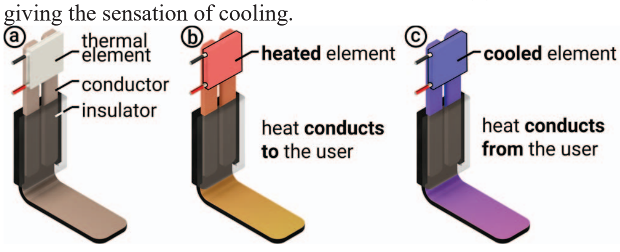

Figure 2: The key technical elements that comprise our approach, i.e., flexible thermal conductors to transfer heat.

ThermalGrasp's approach is different from the traditional approach (which we map in Figure 3)—placing Peltiers *directly* on the user's palm/soles to deliver thermal feedback (e.g., [25], [26], [27], [28]—to cite a few palm devices). Unfortunately, without cooling hardware (heatsinks and/or fans), Peltiers cannot provide sustained cooling for more than a few seconds before residual heat bleeds into the cold side, cancelling out the cooling effect [29]. While brief temperature changes can be effective for feedback like notifications, they cannot provide realistic temperatures needed to render the sense of walking on a gradually cooling floor in VR (e.g., stepping on desert sand that cools as the sun sets, which we demonstrate in *Study 2*). Again, even flexible Peltiers require added cooling to hold cold temperatures [30], [31].

As depicted in Figure 3, our technique **balances** thermal realism and haptic realism from props. While placing a Peltier directly on the palm/sole maximizes thermal realism (sensations are at the palm/sole), one cannot step on or grasp objects with cooling units directly on the palm/sole. Conversely, one could try to place the Peltier element on the backside of this limb to keep the palm/sole free (as in [32] or tactile devices that leave the palm free [33], [34]); however, the thermal realism is now drastically reduced because the sensation is felt at wrong location (opposite-side of palm/sole). Instead, our approach delivers thermal feedback at the palm/sole while only minimally impeding upon real-world interactions, thereby optimizing for *both* thermal *and* real-world haptic realism.

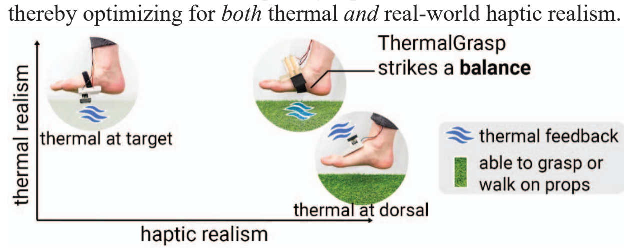

Figure 3: ThermalGrasp balances the realism of virtual temperatures and the realism of haptic props by conducting temperatures from Peltiers using flexible conductive channels, which enables to step or grasp at the application point.

To strike this balance, our approach relocates the bulky yet necessary cooling hardware away from body parts involved with grasping or walking, such as the palms of our hands and the soles of our feet. Then, using robust yet flexible & thin thermal conductors it transfers thermal feedback to the center of the palm/sole. These flexible materials can withstand large forces and wrap around the body—enabling thermal feedback while grasping or walking.

Finally, we tend to think of the devices that we engineered not as end-products but as artifacts of the ThermalGrasp approach—these depict some instantiations of our approach. In the process of creating these devices, we created four additional variations using different types of conductors, which are depicted in Figure 4. Namely, conduction using a copper mesh, a copper netting, a copper tape, and a silicone doped with liquid metal (EGaIn). While in our early technical pilots we found these to have reduced thermal efficiency compared to our final devices using thin flexible copper sheets, these can still be used or serve as a source of inspiration for future thermal devices that also allow grasping and walking.

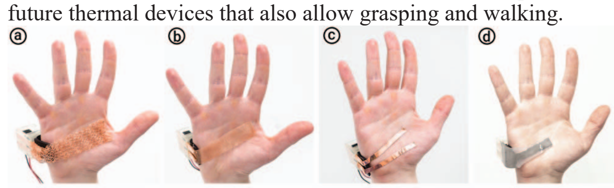

Figure 4: We also explored other conductors: (a) copper net, (b) copper mesh, (c) copper tape, (d) silicone doped with liquid metal.

3 RELATED WORK

The work presented in this paper builds on the field of wearable haptics, with emphasis on devices that allow users to also feel real-world sensations and devices that render thermal feedback. Finally, we succinctly review prop-based passive haptics in VR since these are the key application domain for our technique.

3.1 Wearable thermal feedback = attaching thermal actuators to target area

Researchers have been exploring how to miniaturize thermal actuators into wearable form factors. The most common approach to this challenge has been commercially-available thermoelectric Peltier elements. When electrical energy is supplied to a Peltier, it acts as a heat pump, transferring heat from one side of the device to the other—one side cools while the other heats, depending on the current's direction. This simple electrical control has made Peltier elements easy to deploy in wearable form factors, as shown by *ThermoVR* [35], *LiquidReality* [36], and *TherModule* [37].

However, while Peltier elements are inexpensive and easy to control, they pose disadvantages when applied directly on the user's hands and feet: (1) Peltier elements tend to be thick (~4-6mm typically); (2) Peltier elements are typically rigid (they do not conform well to the body); and more importantly (3) Peltier elements tend to require additional cooling (e.g., large heatsinks and fans). While some wearables have used Peltiers without fans and heatsinks, these are limited to quick notifications [14], [15], [22], and cannot sustain realistic temperatures that are desirable for VR. This is because without cooling, Peltiers can only reliably perform cooling for a few seconds before residual heat from the hot side bleeds into the cold side, which cancels the cooling effect [29]. As such, most interfaces that aim to reproduce the thermal properties of touching an object use dedicated cooling hardware [38], [39]. This limitation has prevented thermal feedback from being applied, for instance, to the sole.

While recent research has led to the advancement and initial commercialization of flexible Peltier elements, these too require fans/heatsinks to deal with their residual heat during/after cooling. Take the Asahi Rubber DK-TEM es-02 [40] flexible Peltier element: its thermal performance was still characterized while attached to a fan and heatsink (3x the area of the Peltier). Moreover, flexible Peltiers remain both expensive and fragile. For example, [40] currently costs $240 a unit (100x a normal Peltier) and has a maximum bending angle of just 115 degrees (i.e., 50 mm bend diameter), which is smaller than even simple human joints, like closing the palm (which folds over itself when making a fist [41]) or curvatures like the arch of the foot (bending angle of 152 degrees while standing [42]).

As an alternative, other types of thermal elements have been explored, such as nichrome wire and conductive fabric [43], [44], [45], which provide resistive heating in a thin form factor but cannot create cooling sensations, thus missing half of our spectrum of thermoception. Some research has instead examined pumping hot and cold fluids for feedback [21], [46], [47]. For example, *HydroRing* [20] delivered temperature-controlled liquids to the fingerpad. Similarly, *Therminator* [19] developed a hydraulic system for thermal feedback on the arm in VR. Finally, *ThermAirGlove* [48] presented a pneumatic glove for grasping *virtual* objects to feel their thermal properties. Thus, while these approaches address the rigidity downside of Peltier elements, they come with their own challenges: **(1) putting moderate forces on a tube will stop the liquid flow** (e.g., if one steps on it, it halts the thermal feedback); and **(2) temperature-controlled fluid tanks have yet to be made wearable**. Faced with the power consumption challenges, others have instead turned to using liquid chemicals to induce illusions of temperature change by chemically stimulating skin receptors to trigger pseudo-temperature changes [49], [50]—still, these chemical approaches are at an infancy (e.g., slow and coarse) compared to expressive and time-tested thermal feedback from Peltier elements and other devices.

In addition to each approach's individual limitations, all these approaches share a conceptual limit: they all apply some form of *thick thermal actuator* (be it a Peltier or a tube) *directly to the area of the user's skin* at the target they wish to stimulate. Here, we observe a conflict with our original goal: to provide thermal sensations yet minimize obstruction to the target area. The closest approach to tackle this is generating phantom heat sensations at the midpoint between two thermal elements [51], [52]; while we find this approach promising and draw inspiration from it, it is limited in that, **(1) the thermal sensations may be confusing**—in fact, to measure the illusion, the "*author instructed the participants to indicate the strength of the sensation perceived on their fingerpad* ***regardless*** *of their perception on the finger side*" [52]—users will feel a spatial mismatch since the sides are hotter than the illusion point, and **(2) the thermal actuators need to be close to the point of the illusion** (e.g., 14 mm; so close that they only add actuators to the side of the fingers in [52], not larger body parts).

Solving this challenge of enabling thermal feedback in conjunction with grasping and walking has, to the best of our knowledge, never been addressed. As such, we looked for inspiration in how researchers have approached this challenge in other haptic modalities, namely those that attempt to provide tactile sensations while keeping the user's hands free.

3.2 Wearable strategies towards haptic feedback while preserving real world sensations

This tension in preserving haptic sensations while interacting with objects is not unique to thermal feedback; in fact, recent research in tactile feedback has focused on engineering devices that minimize encumbering the sensitive areas we use for manipulation, especially the hands [53], [54], [55], [56]. We cluster these strategies, including examples of thermal instantiations, in three categories: (1) *relocated actuators*; (2) *foldable actuators*; and (3) *thin actuators*.

Relocated actuators. One way to preserve tactile sensations is to move the actuator away from the area that will contact an object—this approach is often referred to as *relocated haptics* [57]. The key concept is to still deliver a haptic sensation but not in the location where it is expected to happen. For example, Ando et al. [33] and *Haplets* [34] placed vibrotactile actuators on the fingernail to render feedback that should be felt on the fingerpads. Another example, *Tasbi* [58], moved the actuators even further from the hand by placing them on the wrist. This idea of relocation has been applied to thermal feedback. ThermoFeet placed Peltiers on the dorsal side of the foot to provide directional cues [59]. *Altered Touch* placed its Peltier element on the nail to give thermal feedback while leaving the fingerpad free [32]. Similarly Sato et al. placed its Peltiers on the sides of the fingerpad [52]. As a result, these haptic devices excel in minimizing tactile obstructions (hand/sole free to grasp/walk) but sacrifice this for realism, i.e., the sensation occurs in a location where it is not expected—in fact, to measure this illusion of thermal feedback created from actuators away from the fingerpad, in [56] the "*author instructed the participants to indicate the strength of the sensation perceived on their fingerpad* ***regardless*** *of their perception on the finger side*".

Foldable actuators. A second approach is to use an actuator that provides the haptic effect only when it is necessary but then tucks away while not in use. Examples include a wrist-mounted actuator that taps the palm on-demand [60] and a nail-mounted actuator that taps or *warms up* the user's fingerpad on-demand [61]. Unfortunately, these approaches are only suited for touching either virtual or real objects, but do not allow users to touch both at the

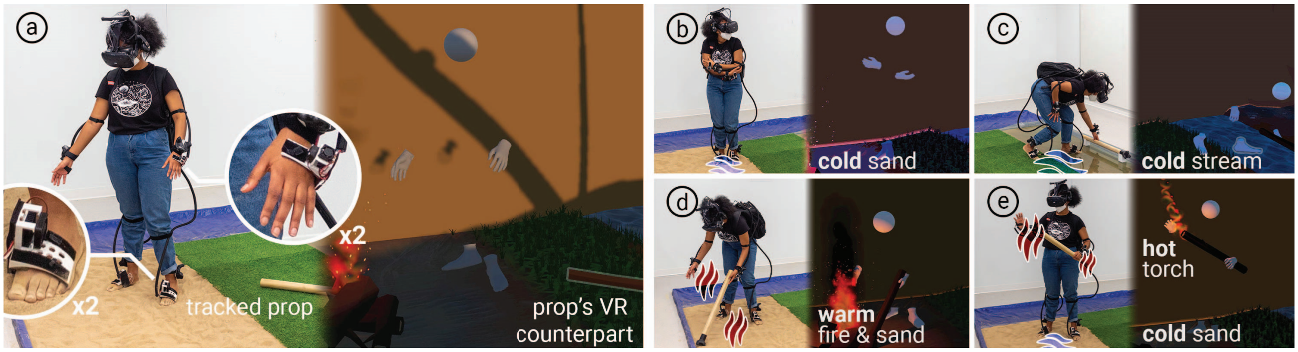

Figure 5: The user immersed in our VR desert survival experience interacts with haptic props such as sand, logs, grass, and water while feeling thermal feedback.

same time—this folding approach does not support augmenting a physical object (such as a VR prop) with thermal sensations.

Thin actuators. The third strategy is to *balance* virtual and real feedback by placing an actuator on the skin area that interacts with objects but making it as *thin as possible*, so that it impedes tactile sensations as little as possible (also referred to as "feel-through" [62], [63]). Examples include an electrotactile device for stimulating the fingerpad via a thin film [63], a latex ring for presenting pressure, vibration, and temperature in mixed reality [20], and hand-worn air bladders that can be in/de-flated on demand [61]. Using this approach, the user does not have full tactile acuity but can still feel objects *through* the thin actuator [62], while also enjoying haptic effects. With respect to thermal feedback, this approach has only been explored by recent flexible Peltier devices [23], [64], [65], which again still require cooling to give sustained/realistic feedback, have limited flexibility, and remain expensive [40] (see section 3.1). ThermalGrasp is directly inspired by the latter by proposing a technical approach that places a *thin thermal conductor* that allows the user to feel thermal feedback and *still grasp or walk.*

3.3 The importance of physical cues even in VR (i.e., props as highly realistic haptic feedback)

In recent years, the use of physical props as proxies for virtual objects has grown popular because they provide cheap yet hyper-realistic haptic feedback [16], [17], [18]. Key to the rise of haptic props is that they can be low-tech; they don't necessarily require expensive actuation or wearables and can be made from readily-available materials (wood, plastic, etc.), yet they can provide sensations very close to their real-world counterparts, such as the weight of a bat [66] or tool [67]. Often, these sensations cannot be produced by common haptic actuators, such as the vibrotactile motors in VR controllers [66]. For example, Franzluebbers et al. found that replacing VR controllers with a golf club prop was preferred by participants and even led to improved VR golf performance [68]. In our work, we strive to allow thermal interfaces and prop-based experiences (VR experiences that rely heavily on grasping and walking) to finally work together.

4 WALKTHROUGH

To help readers understand how ThermalGrasp can present thermal feedback while enabling grasping and walking, we demonstrate it in a prop-based VR desert experience; the user's goal is to survive the night by staying warm. They experience this via physical props, such as tracked handheld props (e.g., wooden logs) or terrain props upon which they can walk (e.g., sand, artificial grass, and a puddle of water). Users wear four ThermalGrasp devices, one on each hand and foot (see Figure 5a).

Figure 5ab depicts that as the sun sets, the user feels the sand beneath their feet getting cold —using ThermalGrasp, the user walks on the real sand while feeling the cooling sensation from the virtual world—this is an example of our how approach improves thermal realism (as shown in Study 2). Walking on sand is possible because the footworn Peltiers and their required cooling units on top of the user's feet (dorsal side) conduct heat to the soles of the feet via thin, flexible copper sheets.

Now, users must survive the desert night by finding a heat source. Figure 5c-d depicts the user collecting wooden logs into a bonfire—their hands grab haptic props (e.g., the wooden logs) and feel the prop's realistic texture. The user even steps into shallow water to grab a log, which would not be safe with Peltiers on the bottom of the feet, as these could short-circuit.

As the user places logs in the fire, the wind blows out the bonfire, scattering the burning logs. The user must now find a new heat source. They search throughout the terrain, while feeling cold on their soles and palms. Finally, they find a scattered log still burning and repurpose it as a torch, as shown in Figure 5e. Upon grabbing the torch, they feel the prop as warmer because the thermal device on the grasping hand heats up due to the virtual flame—an example of how ThermalGrasp allows users to feel the realism of the haptic prop alongside the accompanying thermal sensation. Finally, as the sun rises, the user feels the sand increase in temperature, indicating they survived the desert night.

5 Benefits, Contributions and Limitations

The key contribution of our work is a new method for providing thermal feedback (both hot and cold) in a form that *still* allows for interacting with real-world objects, like grasping props or walking on terrains. The benefit is that this approach **(1) relocates bulky yet necessary cooling hardware to unobtrusive locations**, such as the back of the hands and top of the feet and as a result, **(2) allows users to feel hot and cold sensations and still grasp, walk on, and feel real-world objects**, which is relevant to many interactive domains, such as prop-based VR or AR.

Our approach is not without limitations. First, our approach naturally requires more energy than adding a heat source directly on the target area to reach the same temperature; this is because we conduct the energy over a distance, which requires a thermal gradient where the temperature at the source is more extreme than at the skin. Similarly, because it takes time for the heat to transfer over the distance from the heat source to the target area, our approach is slower than directly placing a heat source on the target area (e.g., a Peltier which can heat and cool at 3°C/sec [15] vs. ours which is <8x slower at cooling and <6x slower at heating as shown in our *device characterization*). While our primary goal is developing thermal devices that enable walking and grasping, we mitigate this lag as much as possible by using heat pipes with high effective conductivities and insulation to reduce losses. That said, we characterized the time to generate a feelable sensation in Study 1 and found that it fits several applications well where slower thermal feedback is realistic (such as radiative heat from fire, gradual temperature changes as the sun sets and rises, and so forth—such as our application for *Study 2*). This is consistent with findings from prior work on slower thermal feedback [69]. However, these are limitations as much as they are tradeoffs, as our approach balances thermal realism with the ability to grasp and walk on surfaces. Finally, because our approach is designed around feeling real-world objects, it is important to note that these objects also have their own temperatures, which interact with the temperatures presented by ThermalGrasp, which may influence perception.

6 IMPLEMENTATION

To help readers replicate our approach, we now provide the necessary technical details. Furthermore, we provide all code and CAD files of our designs to accelerate replication so that others may create devices based on this approach[1].

6.1 Materials

Our ThermalGrasp devices consist of three basic components: hot/cold sources, conductors, and insulators.

Hot/cold sources. For hot and cold sources, we use Peltier elements to be able to render both hot and cold (though our principles of guided conduction would hold for guiding heat from hot/cold liquids, etc.). Moreover, to achieve these realistic, sustained cold sensations, Peltiers require cooling units—we too use a heatsink and fan per Peltier.

Conductors. We use thermally-conductive materials to transfer heat between the thermal element and the user. There are three factors that affect heat transfer in our conductors: (1) materials' conductivities (higher is better); (2) source-sink distance (shorter is better); (3) cross-section (larger is better). Thus, we aim to leverage all factors in our final design to minimize power requirements and improve performance.

We explored various metals and thermally-conductive polymers as conductive channels [70], [71]. Notably, copper boasts a high thermal conductivity (k=~400W/(m·K)) among metals while being low-cost. Thus, we centered our explorations around copper. Specifically, *copper heat pipes* are the key to enabling our technique to work across long distances. Commonly found within computer cooling systems, copper heat pipes consist of a sealed copper tube containing water and wicking material. When one end of the heat pipe is heated, the water vaporizes and naturally travels to the cold end due to the pressure gradient, where it then condenses back into a liquid, releasing the latent heat. The water then returns to the hot end of the pipe via capillary action where the cycle repeats. Notably, this phase change is entirely passive and self-contained (no pumps or fluid in/out)—this gives copper heat pipes an effective thermal conductivity of ~500x that of an equivalent piece of solid copper [72]. While heat pipes are not intrinsically flexible or thin, they are malleable and can be bent into custom shapes. However, heat pipes alone are not sufficient for condensing the bulkiness of Peltier elements into minimally obtrusive thermal actuators. We use them to transfer the heat as far as possible without impeding the user and then transfer the heat into a *thinner conductor*, such as copper sheet metal. To ensure effective heat transfer at all material interfaces, we add thermal paste.

[1]lab.plopes.org/#ThermalGrasp (software, firmware, schematics, 3D files, evaluation scripts)

Insulators. Insulation is critical: (1) insulation around the channels reduces losses to the environment as heat travels through the conductive materials, thus boosting our device's efficiency, and (2) insulation prevents the user from feeling thermal sensations at undesired locations. For example, if we wish to cool the palm, we can insulate the conductors at all points except for the desired point of contact with the skin. Our devices use two types of insulators: rigid plastics (such as PLA, k=~0.13W/(m·K)) for giving structure to the devices and soft foams (such as neoprene, k=~0.05W/(m·K)) which leverage closed air cells as an effective insulator for comfortably interfacing with the user [73], [74].

6.2 Fabrication

We fabricated devices for the palm of the hand and the sole of the foot, as shown in Figure 6. In both designs, we 3D print a form-fitting shell that attaches to the dorsal side of the hands and feet. Peltier elements are placed within the shell and springs are used to press the Peltier's surface to the heat pipes, along with a layer of thermal paste for improved heat transfer. The heat pipes connect to sheet metal that wraps around to the opposite side of the hand/foot. To ensure good contact with the skin, the tightness of the device can be adjusted by sliding the heat pipes up/down in their slots. Additionally, we explored three strategies (all possible) to attach our devices to the body (in order of increasing contact reliability): (1) spring-loading the flexible sheet metal against the foot by enforcing a tight bend radius; (2) adhering the conductor to the skin with skin-safe glue; and (3) wrapping fishing line from the tip of the conductor around the body and anchoring it to the 3D-printed shell. For reliability and ease of donning/doffing, we evaluate designs using the fishing line approach.

Specifically, each design uses the following components: Peltier element (foot: TEC12706, hand: CP60231H), flat copper heat pipes (foot: 70W 11.2 x 3.5 x 100mm, hand: 60W 8.3 x 2.5 x 70mm), copper sheet metal (0.2mm thickness), soft neoprene foam (3.2mm thickness, easily compressible), heatsinks (foot: 40 x 40 x 12mm, hand: 20 x 20 x 10mm), fans (foot: 24V, hand: 12V), and 3D-printed shells[1]. The foot-worn device weighs 145g and the hand-worn device weighs 34g.

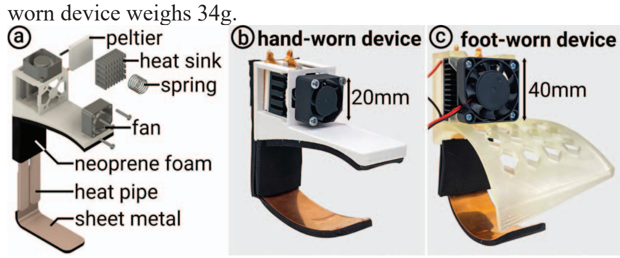

Figure 6: (a) Exploded view and fabricated devices for the (b) hands and (c) feet.

6.3 Sensing, electronics, and PI-controllers

All our wearables feature temperature sensors (100kΩ NTC 3950 thermistors) at the point where the Peltier contacts the heat pipe and where the sheet metal contacts the user—allowing it to monitor the thermal gradient in real-time.

All devices share the same hardware. The Peltier elements are driven by a VNH3SP30 motor controller, which is controlled by an ATmega2560 microcontroller. To combat saturating the Peltier elements in the cooling condition, we use two separate PI tunings for heating (P=75; I=3) and cooling (P=200; I=8). Each controller receives only the temperature at the flexible sheet metal, while the Peltier temperature is used as a safety feature. To achieve rapid temperature change, we use bang-bang control when outside the goal temperature by more than 1ºC in cooling and 2ºC in heating, and the PI controllers when within range of the goal temperature. The fans are triggered programmatically via a MOSFET (RFP30N06LE) when the temperature exceeds the goal. At peak power, one of these devices consumes 25W, which we power via a large LiPo battery worn by the user in a slim backpack.

6.4 Characterizing the performance of our devices

To characterize the performance of our devices created with the ThermalGrasp approach, we tested the heating and cooling performance while wearing the devices.

Temperature stability. We tested the heating and cooling performance on the example of the device for the sole of the foot, as shown in Figure 7. First, to determine the cooling performance, we drove the worn foot device at full power (25W) for five minutes. As shown, the temperature at the point of contact with the foot decreased from 25ºC to 20ºC. In the following five minutes, our controller drove the Peltier element to heat and maintain 40ºC. Finally, to demonstrate the system's stability, we drove the Peltier for five more minutes to cool from 40ºC back to room temperature. Thermal camera images (FLIR C3) were taken of the device's externals to determine the effectiveness of the neoprene insulation. As shown, temperature change was observed at the surface of the insulation (22ºC at end of cooling, 33ºC at end of heating). Considering the Peltier's temperature was 16ºC and 52ºC at these times, heat leakage is expected due to the high thermal gradient.

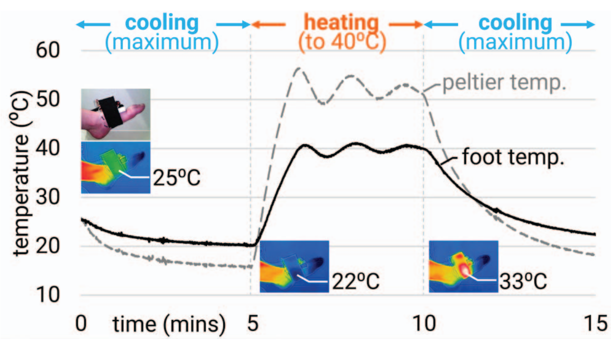

Figure 7: Performance of our ThermalRedirect device for thermal feedback on the sole.

Rate of change. Figure 8 shows temperature over time where our devices contacted the skin. Each device was driven at full power (25W, starting from Peltier at room temperature) for 35 seconds. Moreover, to assist the reader in interpreting this performance characterization, we also show the results of our Study 1, in which we calculated the point at which the average participant felt a temperature change (hand heating and cooling: 11.3 sec, 12.3 sec; foot heating and cooling: 25.2 sec, 16.1 sec).

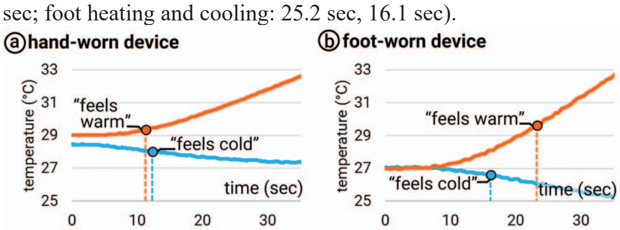

Figure 8: Heating and cooling curves for our (a) hand and (b) foot-worn devices.

It is important to note that while this approach is not as fast as a Peltier directly applied to the skin (i.e., these rates are less than 3ºC/sec exhibited in related works [15]), they are consistent with prior works in which speed is not the goal, yet effective feedback is achieved (e.g., [69]). Instead, our approach generates perceivable temperature changes while still allowing us to grasp and walk on surfaces. Despite this strategic tradeoff, Study 2 demonstrates the value of this approach for conveying realism in VR.

7 User Studies

We conducted two user studies to validate our technique and its implications in interactive applications, specifically in the case of VR. Our studies were approved by our institution's ethics committee (IRB ID anonymous for review).

In our **Study 1**, **we evaluated ThermalGrasp's performance** by first determining if our devices could effectively transfer thermal feedback to the desired location (by sketching the border of sensation over a blank anatomical diagram [75]). Then, we characterized how long it took participants to notice temperature changes while wearing our devices on their hands and feet. The result of this study demonstrated that our approach effectively transfers hot and cold sensations to the user at the target location (comparable to placing a Peltier directly on the target) and is perceivable within an interactive timeframe.

In our Study 2, we compared the participants' sense of realism in a VR task involving *both* real-world and thermal sensations. We found that ThermalGrasp led to improved realism and sensory engagement in VR.

7.1 Study 1: evaluating ThermalGrasp's thermal performance

Our first study focused on characterizing ThermalGrasp's ability to provide thermal feedback. This study assessed (a) the areas of perceived stimulation for both Peltier devices placed on the top and bottom of the foot, along with our foot-worn ThermalGrasp device; and (b) the time it took for the temperature change to be perceivable. Both metrics were evaluated using standardized study designs from psychophysics literature [75], [76].

7.1.1 Study 1a: location of thermal stimulation

We hypothesized that ThermalGrasp provides stimulation closer to the target area compared to placing a Peltier on the dorsal side of the limb but underperforms compared to a directly Peltier on the target area.

Location = foot. We chose to evaluate the foot (rather than the hand) because it represents the more challenging case for existing approaches: (1) virtually no thermal devices can be applied on the soles, since the user cannot step on top of Peltiers and their cooling systems or would otherwise stop the thermal flow for tubes with hot/cold fluids; and (2) the distance from top of the foot to the sole is greater than that of the hand, which pushes ThermalGrasp to its limits more than if we had tested the hand.

Conditions. Participants experienced three interface conditions (in randomized order, across all participants): (1) **direct-peltier** (wearing a traditional Peltier along with heatsinks and fans applied directly to the target area of the sole, the same TEC12706 Peltier as incorporated into the ThermalGrasp design), (2) **dorsal-peltier** (a Peltier applied along with heatsinks and fans to the top of the foot), and (3) our **ThermalGrasp** device (a Peltier on top of the foot, heat transferred via a thin conductor that wrapped from the medial side of the foot to the sole). Thermal contact areas were held constant across all three interface conditions (56 x 27.5mm).

Participants. We recruited eight participants (two identified as female, five as male, one as nonbinary, with an average age of 24.5 years old, SD=1.73). No participants had prior injuries on their feet. Participants received $20.

Apparatus. Participants sat on a chair in front of the experimenter. They could comfortably rest their leg on a stool. Participants were blindfolded so that they could not see the stimulus applied to the foot, nor the thermal device. Participants experienced a cold (20ºC) and hot (40ºC) temperature for each condition. The temperature over time was PID-controlled to follow the same curve for all conditions.

Procedure. When participants felt the 20ºC and the 40ºC stimulus, they were asked to indicate the area where they felt thermal sensations for each stimulus and the point where the sensation was most intense. Participants were provided with a diagram of the foot (sole and dorsal side) and could draw freely; this is a standard method used by prior works [75]. Finally, participants rated the intensity of the thermal sensation (1-7 scale).

Results. Figure 8a depicts our main findings regarding the participants' thermal acuity. For both hot and cold stimuli, **dorsal-peltier** resulted in the area the furthest away from the sole, which implies that dorsal-peltier doesn't present thermal feedback to the sole of the foot. Conversely, **direct-peltier** exhibited the smallest area spread and this area was the closest to the target area (more thermal acuity). While these were expected, it was unknown how **ThermalGrasp** would compare to either of the baselines. We found that **ThermalGrasp** sat between these conditions, exhibiting less thermal acuity than **direct-peltier,** but more than **dorsal-peltier**. This validates our hypothesis. While all participants reported temperature change on the sole during the ThermalGrasp condition, five participants reported sensation on the side of the foot during heating, indicating some heat bleeding through the insulation. Finally, we found no statistical difference between the intensity ratings across all conditions ($p=0.24$ for hot; $p=0.15$ for cold stimuli), which suggests that our apparatus was functioning robustly (all conditions followed the same temperature curves as dictated by our PID controller).

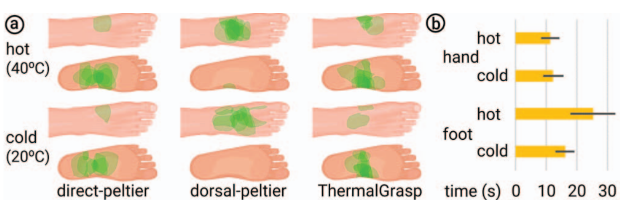

Figure 9: (a) Data (all participants) indicate that participants felt both hot and cold sensations in the desired location of the sole of the foot in the ThermalGrasp condition. (b) Time to notice the change in temperature for both our foot and hand device for heating and cooling. Error bars show standard deviation.

7.1.2 Study 1b: time to perceive thermal stimulation

Having determined that ThermalGrasp could accurately present thermal feedback at the desired locations, we now aimed to find how long it takes participants to experience its temperature feedback.

Conditions. Participants experienced ThermalGrasp on either their dominant hand or foot (counterbalanced).

Participants. We recruited eight participants (three identified as female, five as male, with an average age of 25.1 years old, SD=2.35). No participants had prior injuries on their feet. Participants received $20.

Apparatus. Participants comfortably rested their foot on artificial grass while holding a wooden dowel rod.

Trials. We used two types of trials: **(1) real** temperature, in which our device was actuated to maximum heat/cool, and **(2) placebo** temperature, in which our device was not actuated and stayed at skin temperature. Participants experienced a total of 24 trials (4x repetitions of 3x sensations (cooling/heating/placebo), on 2x body parts (hand/foot))

Procedure. Participants were notified when a trial began. After the experimenter started the trial, a random delay (0-10 sec) was implemented before power was supplied to the device's Peltier. Participants were instructed to confirm using a keypad upon feeling a change in temperature. We recorded the time difference from powering on to the time participants indicated the temperature changed. If participants could not perceive a change in temperature, they were instructed not to press any keys. If a participant did not indicate a change in temperature, the trial would conclude after 45 seconds. Importantly, we purposely included placebo trials in which no stimulation was presented to ensure that participants were not just pressing confirm without no real sensation. Finally, between trials, we waited for the device to return to skin temperature (measured at the sheet-metal) and room temperature (measured at the Peltier).

Results. Figure 8b depicts how long it took participants to notice a change in temperature. For the hand, we found it took on average 11.3 sec (SD=2.9) to notice heating and 12.3 sec (SD=3.3) to notice cooling. For the foot, we found it took on average 25.2 sec (SD=7.3) to notice heating and 16.1 sec (SD=3.2) to notice cooling.

Discussion. We found that participants could feel sensations in under 30 seconds despite transferring the heat over a distance. While this delayed feedback is a limitation for certain applications, it is also exactly what enables being able to walk and grasp while wearing thermal devices. Using these findings, we hypothesized that for interactive applications in which both real-world and thermal sensations are required, our technique will provide users with an improved experience. In our next study, we investigated this with the example of prop-based VR.

7.2 Study 2: Realism in VR

While our first study examined the psychophysics aspects of our approach, our second study focused on observing our approach in an interactive application. Specifically, we assess the extent to which our approach (which allows feeling or walking on props *and* feeling virtual thermal sensations) influences the sense of realism in prop-based VR experiences.

Our main hypothesis for this study was that ThermalGrasp would feel more realistic than a baseline without our devices. Moreover, we were also interested in a range of additional measures typical in studies that evaluate realism of VR experiences, such as immersion (extent to which the experience is inclusive, extensive, surrounding and vivid [77]), enjoyment (taking pleasure in the experience), and sensory engagement (the range of sensory modalities experienced).

Conditions. In this study, participants experienced two interface conditions in counterbalanced order, across all participants: (1) **ThermalGrasp** (four devices, one on each foot and hand) and (2) a no thermal feedback **baseline**.

Participants. We recruited eight participants (four identified as female, three as male, one as nonbinary, average age of 21.8 years old, SD=2.22). None reported injuries on their feet or hands. Participants received $20 for their time.

Task. The VR task mirrored the experience presented in our *Walkthrough*, including all the interactions depicted in Figure 5. The goal for the participants was to find a way to survive the night in this VR desert by building a fire to keep warm. Participants explored this VR experience by walking on the physical terrain shown in Figure 9. The prop-based terrain measured 2.5m x 2.8m with regions of sand, artificial grass, and shallow water. The room was maintained at 22.8ºC. In our experimental condition, participants wore four ThermalGrasp devices, one on each hand and foot. In all conditions, they also wore a wireless HTC VIVE headset, and a backpack with a battery and our devices' controllers, which communicated using Serial over the VIVE's wireless link. Additionally, participants wore a VIVE tracker on each wrist and ankle to track hands and feet. The remaining physical props (wooden logs) were tracked using VIVE trackers.

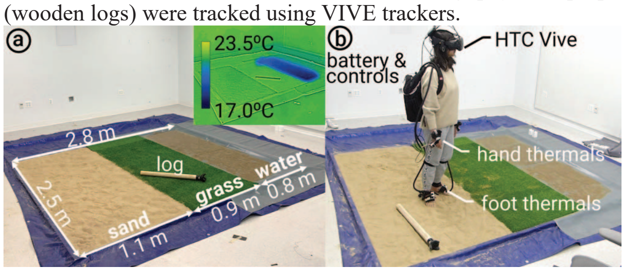

Figure 10: (a) Physical prop-based terrain. (b) Wearable study setup.

Procedure. As participants explored the VR desert wearing ThermalGrasp, their location in the VR world triggered thermal effects. Figure 10 presents the timeline of events alongside the temperatures that participants could experience. The experience's timeline was the same for both conditions, except for the thermal sensations. These timings were designed to ensure a comparable experience across participants and work realistically with our devices' speed. Experimenters added the physical log props into the terrain periodically outside of the participant's field of view, in different locations across conditions. When a participant picked up the log and placed it in the fire, the experimenter "froze" the virtual log's position in the fire and proceeded to move the physical prop to a new location to be collected again. After each trial, participants were asked to report their sense of realism, immersion, sensory engagement, and enjoyment on a 7-point Likert scale, as well as elaborate upon their ratings and the sensations they experienced.

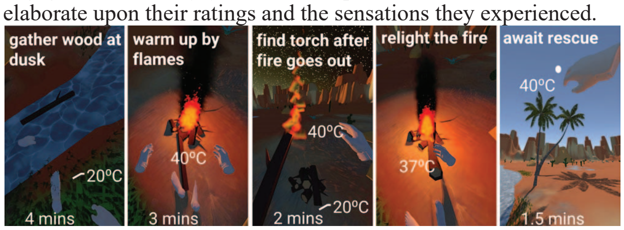

Figure 11: Timeline of events and temperatures (for the ThermalGrasp condition).

Figure 11 presents our main findings. We analyzed our data using a paired T-test (two-tailed). Specifically, **ThermalGrasp** (M=5.63, SE=0.17) was perceived as more realistic (p=0.017) than the baseline (M=4.63, SE=0.30). Similarly, **ThermalGrasp** (M=5.63, SE=0.35) was perceived as more engaging (p=0.009) to the senses than the **baseline** (M=4.63, SE=0.58).

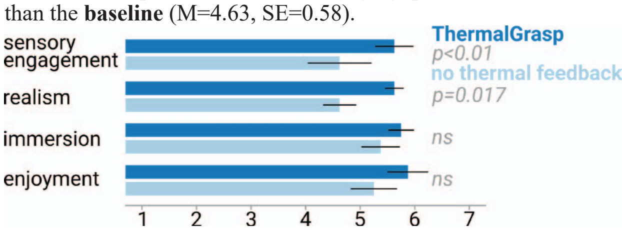

Figure 12: Participants' ratings for both conditions. Errors bars show standard error.

No significant difference was found between the **baseline** and **ThermalGrasp** in terms of immersion (p=0.099; baseline: M=5.38, SE=0.35; ThermalGrasp: M=5.75, SE=0.23) and enjoyment (p=0.090; baseline: M=5.25, SE=0.42; ThermalGrasp: M=5.88, SE=0.37). Finally, five of eight participants reported that they preferred the condition in which they were instrumented with our ThermalGrasp devices.

Qualitative feedback. We analyzed transcriptions of all responses to our open-ended questionnaire. We identified four topics: (1) *thermal referral*, (2) *behavioral change*, (3) *presence* and (4) *preserved grasping and walking*.

Thermal referral. Six (out of eight) participants associated thermal feedback to objects or events in the scene (P1, P2, P5, P6, P7, P8). For instance, P4 reported the temperature of the physical sand being warmer than the grass, even though the sand and grass were at room temperature; it was our device that warmed the feet only when standing on sand. Moreover, participants reported *missing* the thermal feedback when absent: "[baseline led to] a slight disconnect" (P1); "[this experience is] a sensual experimentation and you lose an entire sense [in baseline]" (P7); or "[baseline] felt less like [I was] interacting with the world" (P3).

Behavioral change. We observed behavioral changes in response to the thermal feedback. Notably, heat altered half the participants' relationship to the campfire and its surrounding space (P5, P6, P7, P8). For example, P6 stated "I've got to hold this [torch] so that I'm not near the part that's on fire". P5 also stated that the alignment between the heat and VR situation "feels like something is happening, so you're more encouraged to actually stand by the fire and wait."

Presence. Some participants mentioned their sense of presence increasing based on thermal feedback. P5 remarked that, without thermal feedback, the experience felt like "spectatorship or a loading screen more so than an immersive experience." P3 remarked, "[ThermalGrasp] felt like I was actually taking up space in the environment (…) even though it might seem like a small thing, having that physical feedback […] really affects the experience."

Preserved grasping and walking. Qualitative feedback affirmed that our approach preserves some tactile sensations along with grasping and walking. In both conditions, six participants (out of eight) described the tactile regions in detail (P2, P4, P5, P6, P7, P8). Seven participants (out of eight) reported the textures were unaffected by the thermal devices (P1, P2, P3, P4, P6, P7, P8). P8 detailed their experience by stating, "everything was the same besides adding the heat (…) when I went to pick up the sticks, I didn't have the same feeling on my palm because the device was in the way." Notably, no participant reported any difficulty grabbing or manipulating the tracked prop, no participants reported temperature change felt on the dorsal side of their hands/feet, and no participants reported any discomfort during the experience.

8 Discussion

In Study 1a, we found that ThermalGrasp accurately presented thermal feedback at the desired locations; in fact, with similar performance to adding Peltiers directly on target—however, ThermalGrasp works even while grasping or walking. Conversely, in Study 1b we found that, as expected, ThermalGrasp is slower than directly applying a Peltier to the target, since it requires to transfer heat over distances. Remarkably, in Study 2, we found that this tradeoff between speed and realism can be beneficial, as our participants felt that ThermalGrasp was more realistic and engaging in a VR experience that made use of walking and grasping props.

We see ThermalGrasp as not an end-product, but as an approach to make thermal feedback with props more seamless. Transferring heat over distances has weaknesses for interaction, namely, the rate of temperature change, which may explain why immersion was not greater in Study 2's ThermalGrasp condition. As such, future work can enable wider use cases by improving feedback speed. Several potential avenues to achieve this include:

Increased Peltier/power density. Adding a second Peltier to the design (i.e., sandwiching both sides of the heat pipe) or using higher power Peltier elements will lead to a greater thermal gradient between the Peltiers and the skin, thus increasing the heat transfer.

Spatially-divided hot and cold stimuli. Traditional Peltiers encounter a similar need for rapid temperature changes, especially in scenarios simulating the transition between touching hot and cold surfaces. To overcome the lag of individual elements, a common strategy is to arrange Peltiers in a 2x2 grid with dedicated Peltiers for heating and for cooling. This arrangement enables rapid perceived temperature changes by exploiting two characteristics of human thermal perception: spatial summation and the adapting temperature [78] and has been implemented in various thermal devices [15], [35]. ThermalGrasp can incorporate this arrangement by using multiple Peltiers, each with their own conductive paths meeting in a grid on the skin, to increase the speed of perceived temperature change.

Advanced materials. The bottleneck in our presented hardware is the copper sheet metal. While the heat pipe component transfers heat especially fast, the copper sheet metal has orders of magnitude lower effective thermal conductivity yet is necessary to present the temperature in a thin and conformal interface against the user's skin. Advances in thermal materials may alleviate this bottleneck, such as thin and flexible heat pipes [79], [80], [81].

Beyond this limitation, our work underscores the value of considering thermal latency trade-offs, as our Study 2 found enhanced realism even with this non-instantaneous thermal feedback. Thus, our approach is apt for scenarios expecting non-instantaneous thermal feedback (our Walkthrough/Study 2 used slow thermal feedback, e.g., the sun rising or the flames growing). In our study, we occupied participants (e.g., collecting logs, fire growing visuals) to allow the device time to heat/cool. This strategy is used in haptic displays that require seconds to minutes to actuate, e.g., pneumatic [82] or motor-based [83]. We emphasize that our approach enables an experience that (despite some limitations) is otherwise not possible with traditional approaches: overlaying thermal sensations while grasping/walking on props.

9 Conclusion

We proposed, engineered, and validated ThermalGrasp, an approach for wearable thermal interfaces that enables users to grab and walk on real objects with minimal obstruction. Our approach moves the thermal device and cooling unit to areas not used in grasping (e.g., back of hand) or walking (e.g., top of foot). We then use thin, compliant materials to conduct the device's heating or cooling to the palm of the hand or sole of the foot. Unlike traditional actuators and heatsinks, our thin materials uniquely enable grasping and walking on real objects while enjoying thermal feedback. We demonstrated that our technique can be applied to VR experiences that heavily rely on props or tool manipulation.

We believe that ThermalGrasp points to a direction in which interactive devices aim to harmonize as many senses as possible, while minimizing obstruction to real-world manipulation. Here, we demonstrated how to harmonize thermal feedback and physical interactions. Given the rich haptic properties of real-world objects, we argue users should not have to compromise between choosing to interact with *either* real *or* virtually-rendered sensations.

Finally, we tend to think of the devices that we engineered not as end-products, but as artifacts of the ThermalGrasp approach, which may serve to inspire the creation of new thermal devices that enable interactions with real-world objects. As such, we plan to open-source detailed fabrication, hardware schematics and code to aid future research.

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