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Remapping Wetness Perception in Upper Limb Amputees

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Recent research has made remarkable strides in restoring sensory feedback for prosthetic users, including tactile, proprioceptive, and thermal feedback. Herein, a sensory modality that has been largely neglected is explored: the ability to perceive wetness. Providing moisture-related information to prosthesis users can increase their overall sensory palette toward a more natural sensory experience. A rapid decrease in skin temperature is found to trigger the illusion of contact with something wet. Two body parts were tested, the upper arm and the lateral abdomen, in a group of non amputated participants, and it was found that a wetness sensation can be elicited and maintained for at least 10 s in 86% and 93% of participants, respectively. It is then demonstrated how to mediate the wetness sensation in real-time using a thermal wearable device that mimics the thermal properties of the skin. Finally, two upper limb amputee individuals used their prosthetic arm, sensorized with the device, to discriminate between three levels of moisture; their detection accuracy was similar to one they had with their intact hands. The current study is a stepping stone for future prostheses aimed at restoring the richness of sensory experience in upper limb amputees.

1. Introduction

In the past decade, several research groups have proposed technologies to restore sensory feedback for upper limb amputees.[1–3] These studies have opened the possibility of restoring tactile information via implantable or noninvasive strategies.[4] In a recent study, we have extended the palette of artificial sensory feedback by restoring thermal sensations.[5] Here, we studied a somatosensory modality that has been, so far, very much neglected: wetness perception. Perceiving the presence and extent of moisture in objects could enrich the user's sensory experience and help get closer to a prosthetic replacement that mimics the natural hand.[6] But, to achieve wetness perception with a prosthetic hand, one must first understand how healthy skin detects and perceives the presence of moisture.

Humans do not have specific skin receptors for sensing wetness.[7] Instead, the perception of wetness is believed to be mediated by the integration of afferent inputs from peripheral myelinated A-nerve fibers that are sensitive to cold and mechanical stimulation of the skin.[8] These inputs play a fundamental role in the central neural processing that underlies the ability to sense wetness. Importantly, skin cooling resulting from conductive and evaporative heat transfer is a leading factor for wetness perception.[9] In fact, mechanical parameters, such as friction, have been shown to play a secondary role in wetness perception when compared to the principal contribution of thermal factors.[10] Building on this observation, it has been demonstrated that touching a cold, dry object can generate a wetness

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illusion.[7,9] Our goal is to use this illusory perception to mediate wetness sensation from the prosthetic hand to an intact part of the body (e.g., the upper arm).

First, we identified with 14 nonamputee participants the key parameters of skin cooling (i.e., magnitude, location, and duration) that can reliably trigger a skin wetness illusion. Next, the parameters determined through this first experiment were used to tune a wearable device called the MiniTouch.[5] We used the MiniTouch to detect and mediate different levels of wetness in real-time, and we validated the approach with 8 participants (6 healthy and 2 transradial amputees). As a final proof of concept, we demonstrated that blindfolded amputee participants could successfully use the MiniTouch mounted on their robotic prosthetic hands (RPHs) to freely scan and discriminate samples with different moisture levels in an ecological setting. For the scanning test, to determine whether the wetness levels were detected by thermal cues mediated by the MiniTouch or by mechanical inputs (changes of friction due to the presence of moisture), we compared participants' detection rates when the thermal device turned on or off.

2. Results

We ran three sets of experiments with 20 nonamputee and two amputee individuals. First, we performed the characterization of the wetness sensation on 14 nonamputated participants (7 female), where we investigated whether cold, dry stimuli could produce a wetness illusion (**Figure 1**A). We considered two body parts for this task and tested whether the wetness illusion could be effectively elicited: 1) the ventral upper arm (arm for simplicity in the rest of the text), which is relevant for its proximity to the amputee's residual arm and the prosthetic hand; and 2) the lateral side of the abdomen (abdomen in the text), which bears more cold temperature receptors and is thus more sensitive to lower temperatures.[11,12] For this experiment, we used a commercially available device (TSD191 Thermode), which operated in an open-loop manner. For both body parts, we also checked participants' perceptions of real wet/dry samples.

Second, we investigated real-time wetness sensation with the MiniTouch (Figure 1B) on six nonamputated individuals (3 female) and two transradial amputees (2 male). The MiniTouch is characterized by: 1) an active thermal skin (ATS) sensor, which, as previously described by our team,[5] mimics the skin thermal response by maintaining a surface temperature of 32 °C at a constant power supply, 2) a wearable thermal display (WTD) made of Peltier elements that stay in contact with the user's skin, and 3) a control unit which mediates the thermal feedback from the ATS to the WTD and operates in closed loop.

Third, as a last experiment, we tested the active scanning of wet samples with a prosthetic hand. We placed the ATS sensor on the fingertip of the amputee participants' RPH (2 individuals) and the WTD on their arm (Figure 1C). The participants were blindfolded while using their prosthetic hands to scan samples with three different wetness levels and reported the perceived level of moisture.

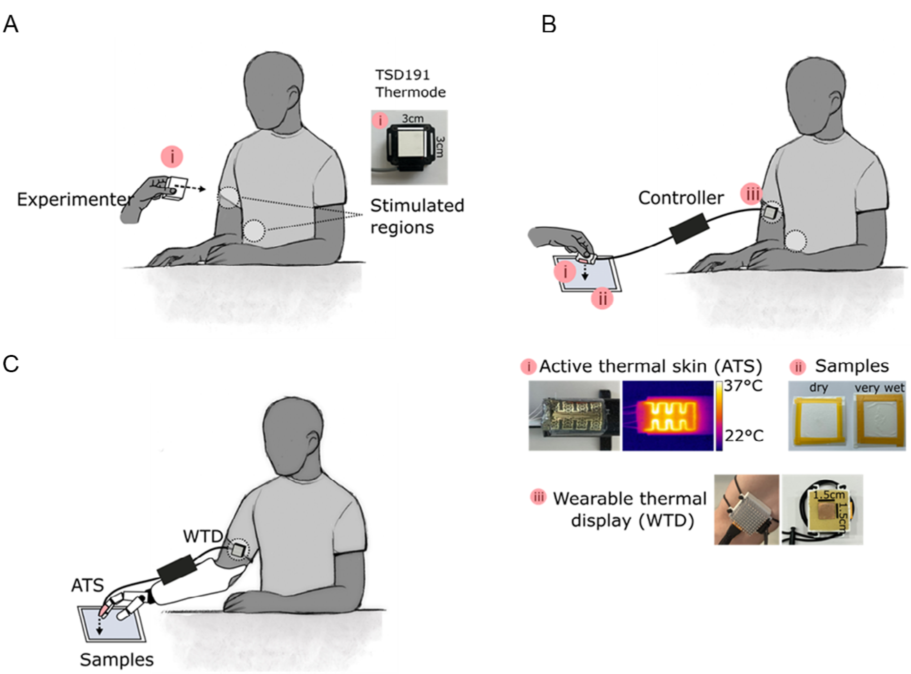

Figure 1. Experimental setup and protocol. A) The wetness illusion characterization was done with nonamputated participants. The experimenter placed the thermode with different temperature inputs (−2, −7, or −15 °C below the participants' skin baseline temperature) on body regions (the ventral upper arm or the lateral side of the abdomen). Participants were blindfolded and their thermal and wetness sensations with a VAS were reported B) For the real-time wetness sensation, we used the MiniTouch system[5]; the experimenter used i) the ATS sensor to scan ii) samples with different levels of moisture. iii) The WTD relayed the thermal drop on the participant's body (arm or abdomen). Participants (blindfolded) reported the perceived wetness level. C) The ATS sensor is mounted on the amputee participants' prosthetic arm, and the WTD was placed on their arm. The participant (blindfolded) scanned samples with different wetness levels and reported their level of wetness.

2.1. Characterization of the Wetness Sensation

We compared the mean responses (visual analog scale, VAS) for all 14 participants for wetness and thermal perception on the arm and abdomen regions considering three temperature inputs: −2, −7, and −15 °C below participants' skin baseline (typically between 32 and 36 °C). First, we investigated the presence of a wetness illusion on both body parts; we found evidence of such perception in 13 out of 14 participants when tested on the abdomen and 12 out of 14 when tested on the arm (**Table 1**). In **Figure 2**, representative examples of a responder (Figure 2A) and a nonresponder (Figure 2B) are presented. We can observe that the thermal perception of the nonresponding participant—in this example, S12 tested on the arm—was similar to the responding participant (Participant S1), suggesting that the lack of wetness illusion was not due to deficient thermal perception. Interestingly, the lack of wetness perception in the simulated wetness experiment was aligned with the poor wetness perception in the physical wetness experiment (Table 1); in other words, participants who did not have the wetness illusion with our setup were the ones with the lowest detection rate for actual wet and dry stimuli.

It is not clear why the generation of the wetness illusion differed among responding participants. We investigated whether the variability of responses could be explained by the physical characteristics of the participants. For this, we compared thermal and wetness ratings for the coldest input (−15 °C) with the following characteristics: participants' body mass index (BMI), body surface area (BSA), and skin baseline temperature (Table S1, Supporting Information). We found a moderate correlation between the baseline skin temperature and the wetness rating in the arm (Pearson coefficient of correlation $r = 0.34$) and the abdomen ($r = 0.32$). We also found a strong correlation between wetness perception and the BMI in the arm ($r = -0.55$) and a moderate in the abdomen ($r = -0.38$) (**Table 2**). In other words, participants with cold baseline skin temperature and participants with high BMI had lower wetness perception.

Table 1. Responses to wetness perception.

Subject	Responder to the wetness perception with dry cold stimuli		% correct detection for physical wet/dry stimuli	
	Abdomen	Arm	Abdomen	Arm
S1	Y	Y	95	100
S2	Y	Y	100	90
S3	Y	Y	100	100
S4	Y	Y	100	100
S5	Y	Y	100	95
S6	Y	Y	100	100
S7	Y	Y	95	100
S8	Y	Y	100	100
S9	Y	Y	100	100
S10	Y	Y	100	100
S11	N	N	75	85
S12	Y	N	100	75
S13	Y	Y	95	100
S14	Y	Y	100	100

Considering only the responders, we found—as expected—a significant effect of temperature input on thermal perception (arm: $\chi^2(2) = 57.42$, $p < .001$; abdomen: $\chi^2(2) = 89.75$, $p < .001$, Friedman test). Participants rated the −15 °C as significantly colder than the −7 °C stimulus (arm: $p < .001$; abdomen: $p < .001$, Wilcoxon rank sum test), which in turn yielded colder ratings than the −2 °C (arm: $p < .05$; abdomen: $p < .01$; Figure 2C). For the wetness ratings, we also found a significant effect of the input temperature (arm: $\chi^2(2) = 57.42$, $p < .001$; abdomen: $\chi^2(2) = 43.7$, $p < .001$, Figure 2D); however, here, while the −15 °C stimulus was rated as significantly wetter than the −7 and the −2 °C (respectively $p < .001$, $p < .001$ for the arm and $p < .001$ and $p < .001$ for the abdomen), no differences were found between the −7 and the −2 °C stimuli ($p > 0.5$ for both body regions). Taken together, these findings suggest that an illusory wetness perception was successfully achieved in both the arm and abdomen regions, with the best results obtained when using the coldest stimuli.

We next investigated whether one of the body regions was a better spot for mediating the wetness perception. As shown, at least one participant had the wetness illusion on the abdomen, while she had none on the arm (S12). We also found that the −2 and −7 °C stimuli were rated on average wetter when applied on the abdomen than on the upper arm (for −2 °C median wetness score for abdomen = 20.37, arm = 9.59, $p = 0.03$) (for the −7 °C, median wetness score abdomen = 21.56, arm = 9.59, $p = 0.04$) (Figure 2D). For the larger temperature drop (−15 °C), we did not observe a significant difference in wetness perception in the two body parts ($p = 0.6$). As such, while the score on the abdomen is slightly better, there is no strong evidence of one body part being better than the other, and both the upper arm and the lower abdomen stay potential candidates.

Considering the −15 °C input stimuli on the responding participants, we found a linear relationship between the thermal perception and the wetness perception ($R^2 = 0.51$ for the arm and 0.52 for the abdomen) (Figure 2E); the more participants perceived a −15 °C stimulus as cold, the more they rated it as wet. Comparatively, we can notice that the nonresponders are outliers to this general trend.

As a last step, we checked if the wetness perception was maintained for longer stimuli or whether it was only a transient illusion upon contact. We compared two time points, upon contact with the skin and 10 s after the sustained contact, for both body parts, considering the −15 °C input and only the responders. We found no significant difference for the arm between the 0 and +10 s conditions ($p = 0.08$, *t*-test), nor for the abdomen ($p = 0.25$) (Figure 2F), suggesting that wetness perception was maintained over time in both body parts. An observation can be made for the thermal perception of the abdomen. The −15 °C stimuli were rated as significantly less cold after 10 s compared to the contact onset ($p = 0.003$). This effect could be due to an actual increase in the Peltier element's temperature after skin contact, given that it was used in an open loop. Interestingly, this temperature difference was not translated to a change in the wetness perception after the 10 s contact period.

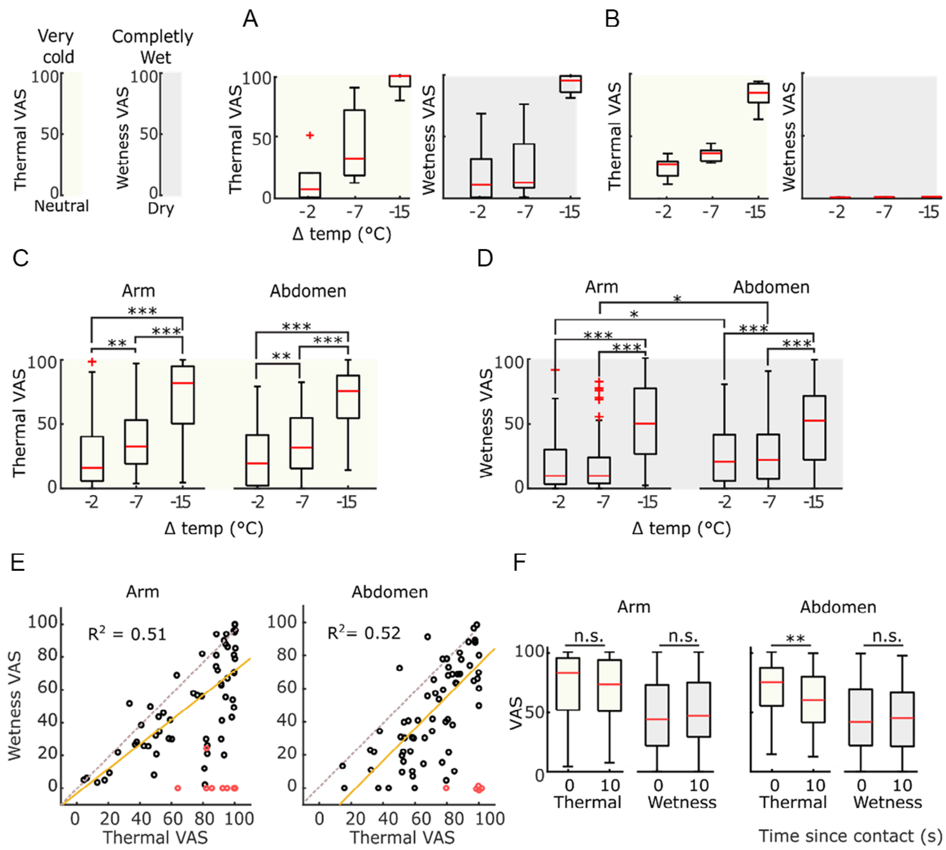

Figure 2. Characterization of wetness sensation via dry cold stimuli Participants responded on a VAS grading for the thermal sensation between 0 (neutral) and 100 (very cold) and the wetness sensation between 0 (dry) and 100 (completely wet). Example of A) responder to wetness illusion and B) nonresponder to wetness illusion via cold, dry stimulation. A nonresponder describes a participant who rated the wetness level as 0 for at least 3 out of the 5 repetitions for all three temperature inputs. C) Temperature and D) wetness ratings upon contact for stimuli applied on the arm and the abdomen. E) Thermal versus wetness perception for all stimuli upon contact on the arm (left) and abdomen (right). All ratings are normalized on a subject-by-subject basis. Black circles are responders, and red are nonresponders to wetness. Yellow line, linear regression on the wetness responders participants. Dashed line $x = y$. F) Temperature (yellow) and wetness (gray) ratings upon contact and after 10 s on the arm pooled over the three stimuli. The boxplots report the median (red line) and the 25th and 75th percentiles, the whiskers extend to the most extreme data points considered non outliers, and the outliers are plotted individually. $^*p < 0.05$, $^{**}p < 0.01$, and $^{***}p < 0.001$. Wilcoxon rank sum test.

Table 2. Coefficient of correlation. Comparison between the VAS score (thermal or wetness) for the −15 °C input and three parameters: (1) B°: skin baseline temperature, (2) BMI: body mass index (kg m^{-2}), and (3) BSA: body surface area (m^2).

	Abdomen		Arm	
	Thermal perception	Wetness perception	Thermal perception	Wetness perception
B°	0.16	0.32	0.01	0.34
BMI	−0.16	−0.38	0.09	−0.55
BSA	0.24	−0.17	0.12	−0.21

To summarize, we found that it was possible to induce a wetness sensation in healthy participants by applying cold stimuli on both the upper arm and the abdomen. We found that different levels of wetness could be achieved depending on how cold the stimuli were perceived and that the wetness perception was maintained for several seconds after contact.

2.2. Real-Time Wetness Sensation

Having validated that cold, dry stimuli can be reliably used to convey wetness sensation on different body parts, we next aimed to demonstrate the possibility of remapping wetness sensation in real-time via a thermode placed on the body and a sensor able to detect different levels of moisture. For this, we used the MiniTouch system.[5] We tested MiniTouch-mediated wetness sensation on the abdomen and the arm with six nonamputee participants and two upper limb amputees (**Figure 3**A). We also measured participants' ability to detect the same levels of wetness when touching samples with their dominant hand's index finger (in the case of the amputee participants with the intact hand).

We found that the nonamputee participants were significantly above chance level in detecting MiniTouch-mediated wetness both on their arm (detection accuracy 53.3%, chance level with $p < 0.01$ is 31.67%, see Experimental Section for chance level calculation) and on their abdomen (62.5%) (Figure 3B). Comparatively, their ability to perform the same task directly

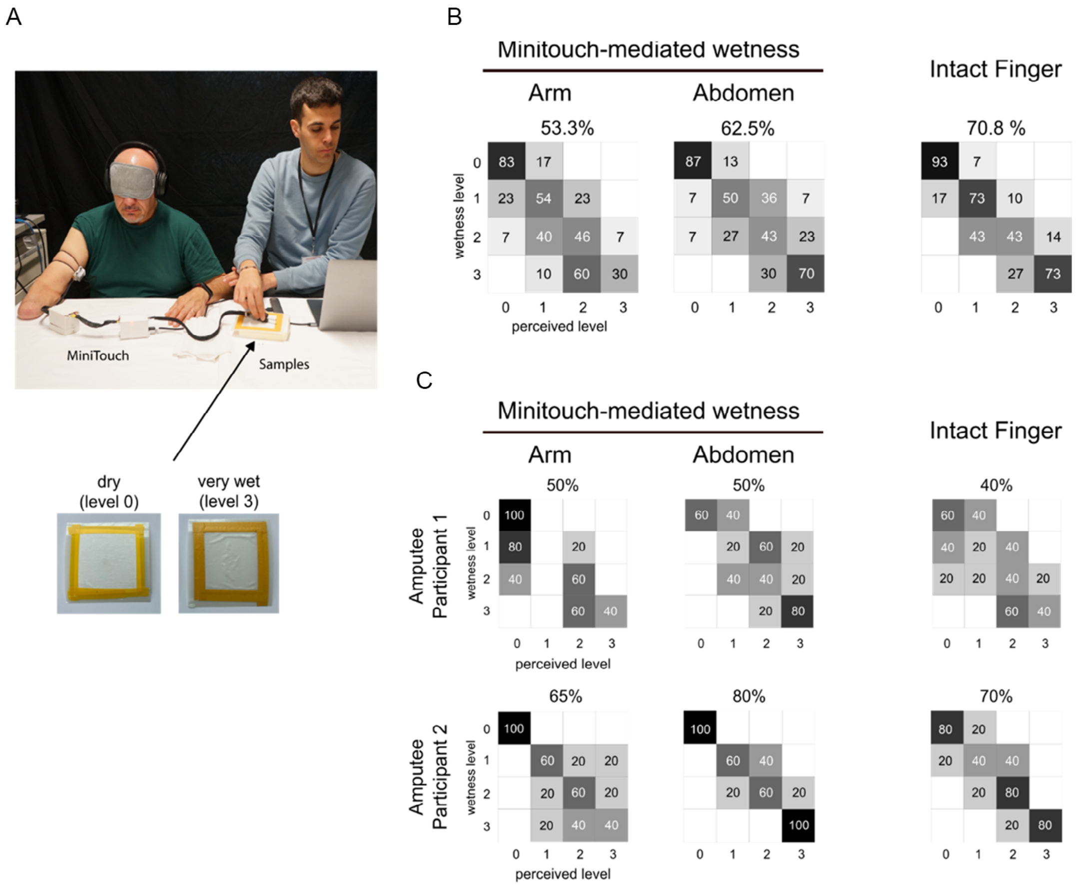

Figure 3. Real-time wetness sensation. A) The experimenter placed the ATS sensor on different samples with different levels of moisture. The participant had to report the level of moisture between 0 (dry) and 3 (very wet). B) Confusion matrices for nonamputated and C) amputated participants.

with their fingertip was 70.8%. At the individual level, 6 participants were above chance ($p < 0.01$) for the abdomen, 4 for the arm, and 6 for the finger.

The first amputee participant had average scores in all three conditions (including the wetness detection with his intact hand: 40%). The scores for the abdomen and the arm were both at 50%. The second participant performed noticeably better in all conditions. Indeed, he correctly detected 70% of the samples with his biological finger and 65% (arm), and 80% (abdomen) when the temperature drop was mediated with the MiniTouch.

2.3. Active Scanning of Wet Samples with a Prosthetic Hand

Two transradial amputee individuals used their RPH sensorized with the MiniTouch to discriminate between different levels of moisture (Figure 4A). For simplicity, we ran the test with three levels (level 0: dry, 0 mL of water; level 1: mid-wet, 2.3 mL; level 2: very wet, 5.8 mL) (Video S1, Supporting Information). The test was performed only on the arm. For both participants, the detection rate was significantly above the chance level (Participant 1: 87%, Participant 2: 80% accuracy; chance level with $p < 0.01$: 60%). Participants' scores when scanning with their intact fingers were 80% and 67%, respectively (**Figure** 4B).

As a control, we also measured the participants' detection rate with the MiniTouch turned off. In this case, the first participant succeeded in only one-third (33%) of the trials, meaning that in the absence of thermal cues, his detection accuracy dropped to the theoretical chance level. Interestingly, the second participant was still able to discriminate the three levels of moisture with similar performances to his natural hand (67%).

3. Discussion

In summary, we have shown the possibility of creating a natural wetness sensation using cold, dry stimuli with two thermal devices and translated this approach to provide a wetness perception to amputee volunteers. We tested two regions as possible candidates for the placement of the thermal device: the ventral upper arm and the lateral abdomen. We have found that the lateral lower abdomen has slightly better results than the ventral upper arm. However, given the relatively small difference between the two body parts, ultimately, the choice of the placement of the thermal device should be made upon development criteria. For instance, the placement on the arm might simplify communication with the thermal device (the thermal device will be closer to the sensor placed on the prosthetic arm); in contrast,

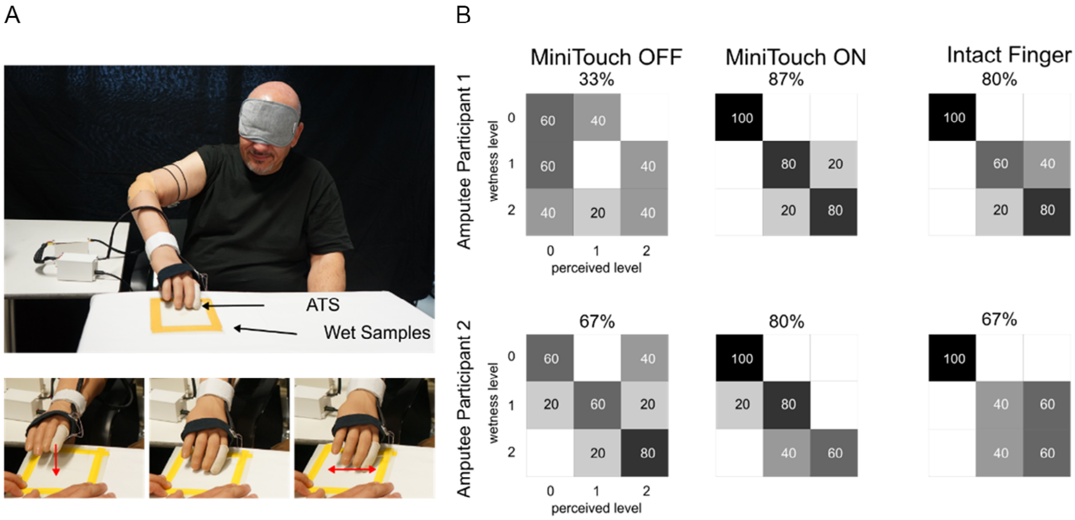

Figure 4. Active scanning of wet samples with a prosthetic hand. A) The participants used their RPH to scan samples with different levels of moisture. The ATS was mounted on the index finger and the thermode on the arm. B) Confusion matrices for the two amputee participants.

placement on the abdomen is less sensitive to the device's weight.

Furthermore, we found that the illusion lasted for several seconds, supporting that it was not only a transient effect. An interesting observation could be made in the abdomen test: while the stimuli were perceived as less cold after 10 s, the level of wetness was judged unchanged. This might be due to the experiential and intuitive knowledge that a cold object may warm up while touching one's skin, but if wet, it can hardly become drier in the short duration of a 10 s contact. The fact that this effect is only observed in the abdomen and not in the arm could be due to the better thermal sensitivity in the abdomen.[11,13] Furthermore, we found that we could simulate a range of wetness perceptions: below a certain threshold, stimuli perceived as more (or less) cold were rated as more (or less) wet.

It was unclear why two participants (out of 14) did not respond to the wetness illusion. Interestingly, these two participants had no issue in rating the cool and cold stimuli; therefore, their lack of wetness perception was not a consequence of impaired thermal sensation. It is worth noting that these two participants also had the lowest discrimination ability when presented with physical wet/dry stimuli. One possibility might be that they relied more strongly than the other participants on the multisensory integration of mechanical cues (when combined with thermal cues) to detect wetness.[10,14] We have recently observed a similar phenomenon when comparing wetness perception between younger and older adults, whereby the latter group presented reduced wetness sensitivity in the presence of intact thermal sensitivity.[15] We hypothesized that age-induced changes in tactile sensitivity might underlie differences in wetness perception in the absence of a thermal effect, a mechanism that could also underlie the outcomes observed in the nonresponders of the current study. We have also found a relationship between wetness perception, BMI, and baseline skin temperature. People with a lower baseline skin temperature likely have less sensitivity to detecting cold stimuli, which is a possible reason for their lower wetness perception. Regarding the negative correlation between BMI and wetness sensation, it has previously been shown that people with high BMI have a higher threshold for painful thermal stimuli in body areas with more subcutaneous fat.[16] Given that our stimulation sites (upper arm and abdomen) are both depots of adipose tissue, a higher BMI and, thus, more subcutaneous fat in these regions could lead to lower sensitivity, which in turn would yield lower wetness perception. Taken together, these parameters could be predictors of patients' potential using a prosthetic that integrates wetness detection. However, further studies are needed to confirm these findings and to test the wetness illusion in different conditions (e.g., ambient temperature and humidity).

Next, we have demonstrated the possibility of mediating the wetness sensation by capturing the thermal drops at the fingertip using a thermal probe and mediating it to a different body part via a wearable thermal display. Finally, we demonstrated, to the best of our knowledge, for the first time, a sensorized prosthetic that allows amputee users to detect different levels of wetness by scanning them. What is more, the subjects' accuracy in this task was similar to their intact hand. Interestingly, one of the two participants (P2) managed to detect three wetness levels above chance, even in the thermal-off condition. He spontaneously reported relying on the sensations conveyed by the RPH on his residual arm during the active scanning. Indeed, studies have shown that even in the absence of cutaneous input in the fingertip (resulting from trauma or Anesthesia), it was possible to discriminate surface roughness,[17] due to friction-induced vibrations propagating in the arm. We believe a similar mechanism could explain P2's ability to detect the levels of wetness above chance in the thermal off condition.

This result is an important step toward building prosthetics to restore the rich sensation of the hand. Detecting wetness through a prosthetic hand could also improve precision grip and object manipulation[6] potentially contributing to more efficient motor functioning. Naturally, wetness sensation is only one component and should be considered in the broader scope of haptic sensation restoration, such as tactile,[1] texture,[18] and thermal feedback.[5]

In the current experiment, the thermal sensation alone was sufficient to give a wetness illusion; however, in our daily experience, we know that not all cold sensations trigger a wetness illusion. Therefore, the question remains: How do we distinguish a cold sensation due to contact with a cold object from one with high thermal conductivity (e.g., copper) and one with a wet object? We have previously demonstrated that wetness perceptions are associated with a specific rate of skin cooling, that is, 0.14–0.41 °C s^{-1} (16). So, the rate of skin cooling provides an important cue to distinguish cold-dry from cold-wet. However, due to the multisensory nature of wetness, thermal and wetness stimuli can be disambiguated consistently only with the addition of tactile cues. It, therefore, appears that, for effective discrimination among thermal-only, tactile-only, and thermotactile stimuli (associated with wetness), a sensing device may need to incorporate an array of thermomechanical sensors that resemble the intact human skin. Therefore, for a complete experience of wetness, we should consider multisensory feedback integration. For this, we can build upon the results reported in the current study and existing noninvasive or invasive technologies, allowing us to provide tactile information.[4]

4. Experimental Section

Participants: Nonamputated: Twenty right-handed healthy young adults (>18 years old) took part in the current study, ten male participants (age 26.8 ± 4.1 year.; BMI 23.5 ± 3.3 kg m^{-2}) and ten females (age 24 ± 1.4 year; BMI 21.9 ± 4.6 kg m^{-2}). Participants had intact cognitive and physiological functions, no evidence or known history of skin disorders, neurological, neuromuscular, or vestibular diseases, and were under no psychotherapeutic or neurologic medication. All participants signed an informed consent form before the experiment's onset. Experiments were approved by the Commission cantonale d'éthique de la recherche (CCER) in Geneva.

Participants: Amputated: Two individuals with transradial amputation participated in the study (male, 57 and 53 years old, with a traumatic lesion). The participants were at the chronic and stable phase of the amputation with good functions of the stump muscle and absence of severe stump pain (pain VAS < 3), with no cognitive impairment, brain damage, or past or current substance abuse disorders. Experiments were performed at the Centro Protesi Inail (Vigorso di Budrio, Bologna, Italy) under the protocol CP-PRO-02-2; the participant signed an informed consent form.

Characterization of the Wetness Sensation: Fourteen nonamputated individuals (seven males (age 27.4 ± 4.6 years; BMI 24.2 ± 3.6 kg m^{-2}) and seven females (age 23.6 ± 1.4 years; BMI 21.9 ± 5.3 kg m^{-2})) participated in the experiment. The participants sat in a chair facing a table. All the stimuli were applied on the nondominant side, either on the ventral upper arm or the lateral lower abdomen (Figure 1A). Participants used their dominant hand to answer to perceptual VAS on a laptop. An S-shaped cardboard panel blocked the participants' sight to their contralateral arm, which was inserted through a window in the panel and rested on the table. To cool down the skin, we used a commercially available thermode (TSD191 Thermode). At the start of the experiment, the room temperature was measured using the thermal probe fixed on top of the thermode to which no voltage was applied; the thermal stimulator was run for 100 s, and the measured temperature was averaged. The participant's skin temperature was measured using an infrared thermometer, and this value was later used as the baseline temperature. We tested three input temperatures in random order: −2, −7, and −15 °C below baseline skin temperature. The trials lasted 10 s, and the participants had to report their wetness sensation at contact and after 10 s of maintaining contact with the Peltier.

This experiment consisted of three phases: 1) familiarization on the fingertip, 2) cold, dry stimulation on the arm and abdomen (randomized order), and 3) physical wetness experiment (same order as in ii). Phase (1) was necessary to introduce participants to the range of the thermal VAS scale. Phase (3) aimed at measuring the participants' baseline perception of actual wet stimuli. The participants were informed that they would receive tactile stimuli on their arms or abdomen and that the stimuli might vary in temperature and wetness. All tests followed the same general structure: the experimenter prepared the stimulus and placed it on the participant's skin, the participant responded to the thermal and wetness VAS, the experimenter dried the skin (even when no wet stimuli were applied) and placed a warm pad in order to return the participant's skin temperature to baseline. Participants were always blinded to the stimuli preparation and application on their bodies. Full details on all three steps can be found in Figure S1, Supporting Information.

The TSD191 Thermode: For the transmission of thermal stimuli, we used the TSD191 Thermode (BIOPAC Systems, Goleta, CA), which comprises a Peltier element of 3 cm × 3 cm contact area and an integrated heatsink and fan to avoid overheating (Figure 1A). The thermode was connected to the STMTHERM thermal stimulator (BIOPAC Systems), which controlled the voltage input leading to the cooling down or heating up of the Peltier. The thermal stimulator was controlled by an MP150 BIOPAC acquisition system, coupled with the Acqknowledge Software (BIOPAC Systems; Acqknowledge version 4.2 for PC/Windows). Using the 'Stimulator Setup' feature, the voltage input to the stimulator was determined. The voltage–output temperature correspondence was characterized to determine the voltage that should be provided for the Peltier element to reach different target temperatures. A thermal probe (TSD202A; BIOPAC Systems) was placed on the contact surface of the thermode, enabling monitoring of the Peltier temperature through the software interface.

The MiniTouch System: The MiniTouch system is a standalone portable thermal feedback device that provides continuous thermal sensations to upper limb amputees. It is composed of three parts: the ATS sensor that measures the characteristic temperature change when touching an object, a control unit, and a wearable thermal display (WTD) that mediates the temperature measurement into a thermal stimulus on the skin of the user. The ATS sensor was a 10 × 20 mm thin polyimide (PI) film that embedded two intertwined platinum (Pt) tracks. The first track was used as a resistive heater to keep the sensor baseline temperature at the human skin level (around 32 °C) while the second track acted as a resistive temperature sensor. The baseline temperature of the ATS sensor being similar to the one of a human finger, the device mimics the human skin temperature change when touching a wet sample. The PI film was bonded onto a polydimethylsiloxane (PDMS) membrane to ease the mounting on a RPH.

The control system consists of two components: a microcontroller (specifically, an Arduino MKR WIFI 1010), responsible for translating the temperature data from the ATS sensor into the desired value for the thermal display, and a temperature controller (Meerstetter Engineering TEC-1091), which manages the control loop. To ensure safety, the system was designed to operate within a temperature range of 15–42 °C. A LiPo battery (Absima, TX LiPo 2 s 7.4 V 1200 mAh) powered the system. The electronics were housed in two 3D-printed cases (50 × 90 × 50 mm) for a total weight of 320 grams (including the ATS, cables and the thermal display).

The thermal display comprised two adjacent Peltier elements (II-IV Marlow, CM35-1.9) soldered on a copper pad (15 × 15 × 0.7 mm). A temperature sensor (TE Connectivity, NB-PTCO-168) was affixed between the thermoelectric modules and a passive heatsink (Fischer Elektronik, ICK S 36 × 36 × 20) dissipated the excess heat generated.

Thermal and Wetness Visual Analog Scales: To evaluate participants' subjective temperature and wetness perception, we asked them to rate both modalities on VAS designed with MATLAB App Designer (MATLAB 2018, MathWorks, Natick, MA). The VAS scales ranged from 0 to 100, corresponding to, respectively, neutral to very cold for the temperature scale and dry to completely wet for the wetness scale. We described a nonresponder to witness a participant who reported a wetness sensation (using the VAS) of 0 for at least 3 out of the 5 repetitions for all temperature inputs.

Real-Time Wetness Sensation: Six nonamputated individuals (three males (age 25.3 ± 2.1 years; BMI 22.1 ± 1.4 kg m^{-2}) and seven females (age 25 ± 0.8 years; BMI 21.8 ± 1.8 kg m^{-2})) participated in this experiment. The participants sat on a chair with their arms placed on a table, and they were blindfolded during the experiment. The WTD of the MiniTouch was fixed either on the participants' arm or abdomen using an elastic cord. Their baseline temperature (B°) was measured at the onset of the session. Each trial started with the experimenter preparing a sample (see below for details), then placing the ATS on the sample for 10 s, and finally removing it. The experimenter indicated the moment of contact with a light tap on the participant's backhand. Participants had to orally report their score between 0 (dry) and 3 (very wet). After the trial, the experimenter dried the ATS and let it return to baseline B° temperature before the next trial could start. Samples with each of the four wetness levels were presented five times in a randomized order, resulting in 20 trials per subject per body part.

The Wet Samples: For the samples, we used polyester-based cellulose cleaning wipes (DYNOclean polyCellWipe 9 × 9) covered with a thin plastic film with a 5 cm hole and sprayed them with water at room temperature. The four levels of wetness were 0 mL of water (level 0), 0.4 mL (level 1), 2.3 mL (level 2), and 5.8 mL (level 3). These levels were defined empirically with one healthy participant (not part of the current study) before the onset of the study; the participant could detect the four levels with 95% accuracy. The participant described level 0 as dry and level 3 as completely wet. Please note that in this study, we were not interested in the precise description of the just noticeable difference threshold for wetness but rather in comparing several conditions of skin/sample interactions for a given set of dry/wet samples. An additional level of 1.1 mL of water was used for the characterization of the ATS response to wet stimuli.

Detecting Wetness Levels with the ATS: We characterized whether the ATS could be used to detect different levels of moisture (based on their thermal drop). For this, we compared the thermal responses of the ATS and the fingertip of one healthy participant (not part of the current study) when in contact with samples with different levels of wetness (Figure S2, Supporting Information).

For the fingertip test, we measured the participant's skin with a thermal probe (Ultra-thin NTC thermistor) placed on their fingertip. We observed a clear drop in skin temperature (−5 °C below baseline B temperature) when in contact with a saturated wet sample (5.8 mL of water on the sample). We observed smaller drops for the samples with 2.3, 1.1, and 0.4 mL and a close to 0 decrease in contact with a dry sample. As such, at the fingertip, the five samples produced five differentiable thermal drops.

For the ATS test, we equally found five separate thermal drops but with approximately twice the amplitude of response compared to the finger due to the smaller thermal inertia of the ATS compared to the finger. Notably, the responses of the fingertip and the ATS were highly correlated ($R^2 = 0.99$). The linear relation between the thermal drop at the fingertip and the ATS was given by $y = -0.03 + 0.49X$. Accordingly, and considering that the offset is negligible, we set $\Delta T(\text{WTD}) = 0.48 * \Delta T(\text{ATS})$, where $\Delta T(\text{WTD})$ (respectively $\Delta T(\text{ATS})$) is the temperature drops of the wearable thermal display controlled by the control unit (respectively the temperature drop measured by the ATS sensor).

Active Scanning of Wet Samples with a Prosthetic Hand: The participants (two upper limb amputees) used their RPH to scan samples with three different levels of moisture (level 0: 0 mL, level 1: 2.3 mL, and level 2: 5.8 mL). For this, the ATS was mounted on the index finger of the participant's personal prosthetic hand (Michelangelo hand and MyoHand VariPlus, Ottobock SE & Co. KGaA). We presented each level five times in a randomized order. For each trial, the experimenter prepared the sample and then asked the participants to raise their arms. The experimenter placed the sample under the participant's finger and informed him to start the scanning. The participant was allowed to scan the sample with their prosthetic finger for 10 s and then reported the perceived level of wetness orally. As a control, we ran the same with the MiniTouch turned off. Finally, we also measured the participant's detection rate when scanning the sample with the index finger of his intact hand.

Calculation of the Chance Level: In classification tasks, the theoretical chance level for infinite sample size and n classes is $1/n$. Yet, for experiments with a relatively low number of trials, it is not so unlikely that the participants exceed this theoretical level by randomly classifying the stimuli. Here, we evaluated the statistical significance of the performances obtained by assuming that the classification errors followed a binomial cumulative distribution.[19] We estimated the percentage accuracy that could be achieved with random answers for a certain p-value. For instance, considering the results of the six healthy participants together (6 participants × 20 trials = 120 samples, 4 classes), the probability of reaching at least 31.67 % of correct answers was lower than 1 out of 100. Hence, we considered that the chance level associated with $p < 0.01$ was 31.67% for the group results. When considering the performance of the individual participants (20 samples, 4 classes), we found a chance level ($p < 0.01$) of 50%. Similarly, for the active scanning task (15 samples, 3 classes), the chance level with $p < 0.01$ was estimated at 60%.

Samples Preparation: The levels of moisture were prepared by spraying water at room temperature on cloth samples (DYNOclean polyCellWipe 9 × 9). The clothes were cut into 11 cm squares and fixed onto a plastic sheet with tape on the four sides to prevent water spillage. An additional plastic sheet with a 5 cm diameter hole was placed on top of the sample to limit the amount of water reaching the surface. The experimenter used two boxes (10 and 25 cm high) with a hole for the sprayer nozzle (Pump Sprayer 0.75 L, Gardena) on their top face to guarantee the reproducibility of the moisture levels. Alignment marks on the table allowed the positioning of the samples under the boxes. The number of sprays and the distance to the sample were defined to reach different wetness levels (Table S2, Supporting Information). The four main levels used in the study ranged from completely dry (level 0) to very wet (level 3). An additional intermediate level was defined for the characterization of the ATS response to different wetness levels (see detecting wetness level with the ATS). Once the samples were prepared, the experimenter waited 60 s to ensure a uniform impregnation of the cloth before presenting it to the participant.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

F.I., J.M., O.A., S.M., and S.S. are co-inventors of a thermal sensing device and sensory feedback system and method using said thermal sensing device (application number EP22207038.5).

Author Contributions

M.P., J.M., D.F., S.M., and S.S. took care of conceptualization; M.P., J.M., A.F., N.C., and S.S. took care of analysis; Development of the portable thermal device: J.M., F.I., O.A., S.M., and S.S. took care of development of the portable thermal device; M.P., J.M., A.F., N.C., F.I., and F.M. took care of investigation; F.M., E.G., and S.S. took care of clinical tests; M.P., J.M., S.M., and S.S. took care of visualization; S.M. and S.S. took care of supervision; Writing the original draft was done by M.P., J.M., and S.S.; Writing the review and editing by A.L.L.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

prosthetics, sensory remapping, wetness perceptions

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