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Research article

Effects of water immersion on sensitivity and plantar skin properties

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ABSTRACT

Skin, as the largest organ of the human body, has various important functions, like protecting from dehydration or preventing the intrusion of microorganisms. Certain external factors have been shown to negatively influence skin functions. One of those factors is long-term (several hours) exposure to liquids, such as water, leading to skin softening. This study aimed to examine whether detrimental effects, such as skin softening, already exist after short-term water exposure. Furthermore, we investigated whether cutaneous sensation is altered by short-term water exposure. Thirty healthy subjects participated in this study (23.1 ± 2.5yrs, 173.7 ± 8.5 cm, 67.5 ± 9.8 kg). First, vibration perception thresholds (VPTs; 200 Hz), the skin´s elasticity (logarithmic decrement), and the skin´s mechanical deformation resistance properties (durometer readings) were measured at the plantar aspect of the hallux and heel of both feet (pre). Subsequently, one randomly chosen foot was immersed in water (45 min; water temperature adjusted to the foot pre temperatures). The contra-lateral foot remained untreated and out of the water. After the intervention, all three above-mentioned parameters were measured again in the same manner (post). Inferential statistical tests to detect differences regarding elasticity, durometer readings, and VPTs were performed based on logarithmically transformed data (natural logarithm). VPTs did not show significant differences. However, an overall increased elasticity and a softening effect of the skin were evident due to the water exposure at both anatomical locations. This study showed that 45 min of water exposure induces changes in plantar skin properties similar to the long-term effects described in other studies. Most importantly, the short-term water exposure resulted in a softening effect, which may affect skin perfusion in a negative manner. This may facilitate skin irritations and even future ulcer formation. We also showed that changes in mechanical skin properties induced by water exposure did not influence plantar cutaneous sensation. The findings of this study are especially relevant for people with impaired skin recovery mechanisms and highlight the importance of keeping skin dry, particularly in people who are bedridden.

1. Introduction

Skin, the largest organ in the human body, is responsible for various functions, like preventing the intrusion of microorganisms and protection from dehydration [1]. Skin also contains various sensory receptors, e.g. free nerve endings and cutaneous mechanoreceptors. These receptors allow us to actively interact with the environment. In particular, the importance of plantar cutaneous receptors on posture is well established, e.g. [2]. Skin sensitivity decreases with increasing age [3] or with disease, such as diabetes mellitus [4]. This negatively impacts balance [4], and may facilitate ulcer formation [5]. Free nerve endings provide information when harmful stimuli are delivered toward the skin. In healthy subjects, noxious stimuli usually result in nociceptive reflexes [6]. In people with a severely reduced protective function of the skin, nociceptive reflexes may be slower or even be missing. Consequently, mechanical (or heat) stimuli applied toward the skin may be missing due to receptor and/or nerve damage. Since skin recovery mechanisms are impaired in those patients, skin ulcers may be the consequence which lead to considerable restrictions of daily activities.

Not only plantar sensitivity, but also plantar mechanical properties of the skin have been investigated. There are studies examining plantar skin mechanical properties (e.g. [7]), plantar tactile sensitivity (e.g. [8]), or both (e.g. [9]). Lin et al. [7] found that plantar shear stiffness is highest at the level of the skin, and decreases with increasing depth of the tissue. There have also been questions about how plantar skin sensitivity may be influenced by various skin mechanical properties. It was shown that plantar sensitivity [8,10] and skin mechanical properties [9] are different across the foot sole, but skin sensitivity does not significantly correlate with skin mechanical properties [9]. Hence,

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changes in skin sensation cannot (solely) be attributed to differences in skin mechanical properties, such as hardness or thickness [9].

Skin contact with various liquids was also identified as a factor which may influence different skin properties [11], and eventually lead to skin maceration [12]. Not only hot substances or chemicals exhibit detrimental effects, but also urine, perspiration, or even water [13–15]. The latter was found to soften the skin and increase the vulnerability of underlying blood vessels to pressure-induced blood flow reductions [13]. It is possible that the skin softening effect co-exists with the reduced blood flow observed. In other studies, increased abrasion damage, skin irritations, which may result in ulcer formations, or other damage were found when subjects were repetitively exposed to urine or perspiration [14,16–18]. Such findings may play an important role for people who are bedridden some or all of the time. In particular, it was presumed that bed rest of 14 days resulted in changes in pressure sensitive cutaneous receptors [19]. However, we found no studies examining short-term effects of water exposure on skin properties. Furthermore, ulcer formation may also be promoted by decreased skin sensitivity, where noxious (mechanical) stimuli are not adequately perceived. Regarding skin sensitivity, vibration perceptions thresholds (VPTs) have been identified as a reliable parameter to identify diabetes patients and even to identify the risk of plantar ulcer formation [5,20].

It was also shown that VPTs depend on skin temperature [8,21,22]. To cool the skin, including its receptors, protocols often include water exposure. Long-term water exposure leads to skin softening [13,18], which additionally may dampen vibratory stimuli, resulting in increased VPTs. Again, we found no study which has explicitly examined the effects of water immersion on plantar VPTs. If such an effect were proven, the common interpretation that reduced VPTs occur after skin is cooled by water may not be that definite, and the indicating contribution of VPTs to detect risks for ulcer formation may be biased. Therefore, this study examined the effects of short-term plantar water exposure on VPTs and various mechanical skin properties. We hypothesized decreased skin sensitivity, increased elasticity, and decreased mechanical skin deformation resistance following short-term exposure of the plantar foot to water.

1.1. Material and methods

1.1.1. Subjects

Thirty subjects (13♀, 17♂) participated in this study (mean ± SD: 23.1 ± 2.5yrs, 173.7 ± 8.5 cm, 67.5 ± 9.8 kg), and were free of lower extremity pain and injuries for at least 6 months prior to testing. Subjects were also free of neurological diseases like diabetes mellitus, neuropathy, or Parkinson´s disease. They showed normal plantar skin properties and no signs of open wounds, ulcers, impurities, or reddened, itchy, dry, or rough skin. Participants were informed about the purpose of this study. They gave their written informed consent and were free to withdraw from the experiments at any time. This study was conducted according to the recommendations of the Declaration of Helsinki and was approved by the Ethics Committee of the Faculty of Behavioural and Social Sciences of the corresponding university.

1.1.2. Instrumentation

Plantar, water, and room temperatures were measured using a digital type-K-thermocouple (PeakTech 5135, Germany). To assess plantar skin sensitivity, VPTs were measured using a Tira Vib vibration exciter (model TV51075, Germany), powered by a Voltcraft oscillator (model FG 506, Germany). The vertical movement of the vibration exciter's contactor (diameter 7.8 mm, 2 mm above the surrounding aluminum platform, see [8,23]) was laser-calibrated to obtain direct readings of the vibration amplitude. To reach the subjects´ plantar skin, the contactor protruded through a hole in a heatable aluminum platform, which was adjusted to the subjects´ plantar temperature to avoid plantar skin temperature fluctuations. This was necessary, since skin temperatures are known to influence skin sensitivity [8,10,22]. During the measurements, subjects evenly placed their feet on top of the aluminum platform which functioned as the footrest. The frequency of the vibrating contactor was 200 Hz, which is known to be within the optimal stimulus range to elicit fast-adapting mechanoreceptors of type II (FA II, Vater-Pacini-corpuscles) [24]. The vertical force applied from the subjects´ feet toward the contactor was monitored via a force transducer and kept within a range of ± 0.5 N.

The MyotonPRO device (Myoton AS, Estonia) and a durometer (AD-100-OO, Checkline Europe, Germany) were used to assess mechanical properties of the plantar tissue. The handheld myoton device consists of an impactor (diameter approx. 3 mm) which touches the skin in five consecutive repetitions per trial (pre-compression 0.18 N, impulse force 0.4 N, duration 20 ms, respectively). The myoton analyses the naturally damped oscillation following the deformation caused by each impulse. The logarithmic decrement (log D) of the natural oscillation was used to characterize tissue elasticity. Since the elasticity is inversely proportional to the log D, tissue elasticity increases as log D decreases [25].

Furthermore, a durometer (Shore OO) was used to assess the skin´s mechanical deformation resistance properties, often mistakenly referred to as skin hardness. This handheld device was applied perpendicularly with respect to the anatomical location. Based on the probe´s penetration depth, the analogue scale of the device (shore scale range from 0 - softest to 100 - hardest) provided arbitrary units, which were sampled as measurement results.

1.1.3. Testing procedure

Before the tests, each subject acclimatized to the room temperature (23 ± 2 °C, EN ISO/IEC 17025) for 10 min (without the feet touching the floor). Afterwards, the participants´ right or left foot was randomly assigned as either control (CF) or intervention foot (IF). Anatomical locations were marked with a pen.

First, baseline measurements were performed at the plantar heel and hallux (middle point) of both feet prior to the intervention (pre). Regarding VPTs, subjects were in a quiet room wearing noise cancelling earphones (Quiet comfort 20i, Bose, USA) to avoid distractions during the measurements. All participants were in a sitting position with an ankle, knee, and hip angle of approx. 90°. They rested their arms on top of their thighs, close to the abdomen. Subjects were instructed to sit standardized but also comfortably to be able to concentrate on detecting the vibration stimuli. VPTs were measured similar to a Method of Limits approach as introduced by Mildren et al. [26]. In total, three VPT trials were collected at the heel and hallux (barefoot) of both feet. Plantar temperatures (PTs) were also measured at the heel and hallux of both feet. For log D and durometer readings, subjects were in a prone position with their lower legs and feet slightly elevated to approx. 60° by adjusting the footrest of a common patient couch. This enabled the myoton and durometer to be operated comfortably and accurately (vertical alignment with respect to anatomical location, no foot movements). Three trials were collected at each anatomical location of both feet.

Second, a bowl of sufficient diameter was used to perform the water intervention for IF. Pre PTs (mean of hallux and heel temperatures) were used to adjust the water temperature to avoid discomfort and temperature-related changes in VPTs. IF was immersed up to the ankle and the intervention lasted 45 min for each participant. Meanwhile, water temperature was monitored and warm water was added to keep temperatures constant throughout the intervention. Subjects sat with the CF resting next to the bowl on top of insulating material to prevent temperature changes. After the intervention, the IF was removed from the water and immediately dried using a towel.

Third, all measurements (PTs, log D, durometer readings, and VPTs) were repeated after the intervention (post) as described above. Anatomical locations were randomized, but not the order of measurements.

1.1.4. Data analysis and statistics

For all data, means ± standard deviations (SD) were calculated based on the three trials for each anatomical location of both feet (CF, IF). Data analyses were conducted using R (The R Foundation for Statistical Computing). The Shapiro-Wilk-test was used ($\alpha = 0.05$) to test data distribution. Differences for the hallux and the heel were analyzed using Wilcoxon and dependent t-tests. The level of significance was Bonferroni-adjusted due to the number of pairwise comparisons from $\alpha = 0.05$ to $0.05/6 = 0.0083$. As recommended [27], all statistical tests were performed on logarithmically transformed data (natural logarithm, log) for VPTs, log D, and durometer readings after confirming that data benefitted from the transformation. Data of log D, durometer readings, and VPTs mentioned in the text, in tables, or in figures are illustrated as raw, untransformed data to allow for better reading and interpretation.

2. Results

Since no statistically significant differences were found between genders, female and male participants were analyzed together.

2.1. Water and skin temperatures

Water temperatures exhibited significant ($p < 0.001$) differences: 28.2 ± 1.3 °C (pre) and 27.0 ± 0.8 °C (post).

PTs (mean ± SD) differed significantly ($p = 0.003$) between 26.9 ± 2.1 °C for the intervention foot (pre) and 25.8 ± 1.5 °C for the control foot (post), but only for the heel (Table 1).

2.2. Mechanical properties and skin sensitivity

Log D exhibited significant differences (Fig. 1): For the hallux, post IF (0.829 ± 0.118) was significantly lower compared to post CF (0.955 ± 0.130; $p < 0.001$), pre CF (0.910 ± 0.102, $p < 0.001$), and pre IF (0.924 ± 0.141, $p < 0.001$). For the heel, the same findings were observed: Post IF (0.922 ± 0.142) was significantly lower compared to post CF (1.021 ± 0.144; $p < 0.001$), pre CF (1.034 ± 0.149, $p < 0.001$), and pre IF (1.044 ± 0.189, $p < 0.001$).

Durometer readings (Fig. 2) for the hallux revealed that post IF (32.9 ± 6.7) was significantly smaller compared to post CF (35.6 ± 6.4, $p < 0.007$) and pre CF (36.3 ± 6.0, $p = 0.007$). Post IF (32.9 ± 6.7) was smaller than pre IF (34.3 ± 6.6), but the difference was not significant ($p = 0.011$). For the heel, post IF (37.4 ± 6.5) was significantly smaller compared to post CF (41.2 ± 6.3, $p = 0.007$). The other comparisons did not exhibit significant differences, although post IF (37.4 ± 6.5) was descriptively smaller than pre IF (39.1 ± 5.8, $p = 0.036$) and pre CF (39.0 ± 5.9, $p = 0.080$). Regarding skin sensitivity, there were no statistically significant differences for anatomical location or group (Table 2). For the heel, VPTs ranged between 1.9 ± 0.9 and 2.3 ± 1.1 µm. For the hallux, VPTs ranged between 1.6 ± 1.3 and 1.9 ± 2.1 µm.

3. Discussion

This paper investigated the effects of short-term water exposure (45 min) on mechanical and sensory properties of the plantar foot. Water exposure increased elasticity of the skin and induced a softening effect. VPTs remained unchanged.

3.1. Water and skin temperatures

We tried to maintain water temperatures at constant levels by adding warm water, and by additionally insulating the bowl, but water temperatures decreased significantly by 1.2 °C (pre: 28.2 ± 1.3 °C, post: 27.0 ± 0.8 °C, $p < 0.001$) throughout the intervention duration.

However, this did not affect PTs, possibly due to thermoregulation. PTs were only significantly different at the heel (Table 1). Skin sensitivity strongly depends on skin temperatures [8], and Schlee et al. [10] demonstrated that ± 5 °C is sufficient to alter skin sensitivity. A microneurographic study also showed that decreasing skin temperatures reduced plantar cutaneous afferent firing responses [28]. We found that (a) the fluctuations of PTs were very small (mean difference: 1.1 °C), and (b) the significant fluctuation in PTs was only present in one out of 12 statistical comparisons. Therefore, we presume it did not influence skin sensitivity.

3.2. Mechanical properties and skin sensitivity

Confirming our hypothesis, significantly reduced log D values were evident when comparing IF post to all other measurements (IF pre, CF pre, CF post), for both anatomical locations. This highlights that water immersion itself is responsible for this finding. Since log D is inversely proportional to tissue elasticity [25], water increased the skin´s elasticity, which is similar to findings from another study [29]. As mentioned above, this can be explained by the skin´s ability (especially epidermis) to take up water [30] resulting in a thickening and swelling. Water is accumulated in intracellular spaces, and corneocytes swell [31]. Furthermore, water disrupted the intercellular lipid structures and led to a three to four-fold increase in the stratum corneum thickness [32] and skin became more elastic. Durometer readings showed some significant differences confirming our hypothesis: Post measurements for IF were associated with significantly smaller values compared to post CF (for heel), and compared to post CF and pre CF (for hallux). Descriptively, the other comparisons confirm smaller durometer readings due to water as a trend. Hence, those results affirm that water immersion resulted in reduced mechanical deformation resistance properties, suggesting a "softening" of the skin. In addition, skin wetting induced by water caused an increased skin permeability to noxious substances [33,34]. This contributes to the breakdown process of skin [13], likely accelerates the development of skin irritations, and presumably the development of future ulcers. Hydration of the stratum corneum may contribute to allergic and irritant contact dermatitis [35,36]. Skin wetness also led to increased abrasion damage and microbial growth [14], and decreased the pressure required to compress nailfold capillaries [37], thus disturbing blood supply. There is a strong relationship between excessive skin wetting, regardless of origin, and pressure ulcer formation [38]. Liquid exposure is known to change physiological functions of the skin [11,12,15], likely resulting in skin diseases [39]. Mayrovitz and Sims [13] exposed subjects to water and artificial urine (5.5 h). They also found a softening effect and conclude that decreased tissue hardness renders tissue perfusion more vulnerable to pressure loads. We also found this softening effect, however, after only 45 min. A recent study identified water alone as a direct pathogenetic factor [40]. Further, Mayrovitz and Sims [13] found that wet skin showed reduced temperatures compared to dry skin. In contrast, the water temperature in our study was adjusted to PTs. However, water temperatures may not be adjusted in many everyday situations. Consequently, reductions of skin sensitivity and an absence of protective reactions may lead to increased risk of irritations or ulcer formation.

Regarding the magnitude of VPTs, this study is in line with previous investigations (e.g. [8,22]), and vibration amplitudes as small as

Table 1
Plantar temperatures (mean ± SD) measured at the heel and hallux before (pre) and after (post) 45 min of water immersion. CF = Control Foot, IF = Intervention Foot. Significant differences: *$p = 0.003$, $\alpha = 0.0083$.

	CF (Mean ± SD)		IF (Mean ± SD)	
	Pre	Post	Pre	Post
Heel (°C)	26.8 ± 1.8	25.8 ± 1.5*	26.9 ± 2.1*	26.3 ± 1.4
Hallux (°C)	26.6 ± 2.8	25.5 ± 2.1	26.6 ± 3.2	25.5 ± 1.5

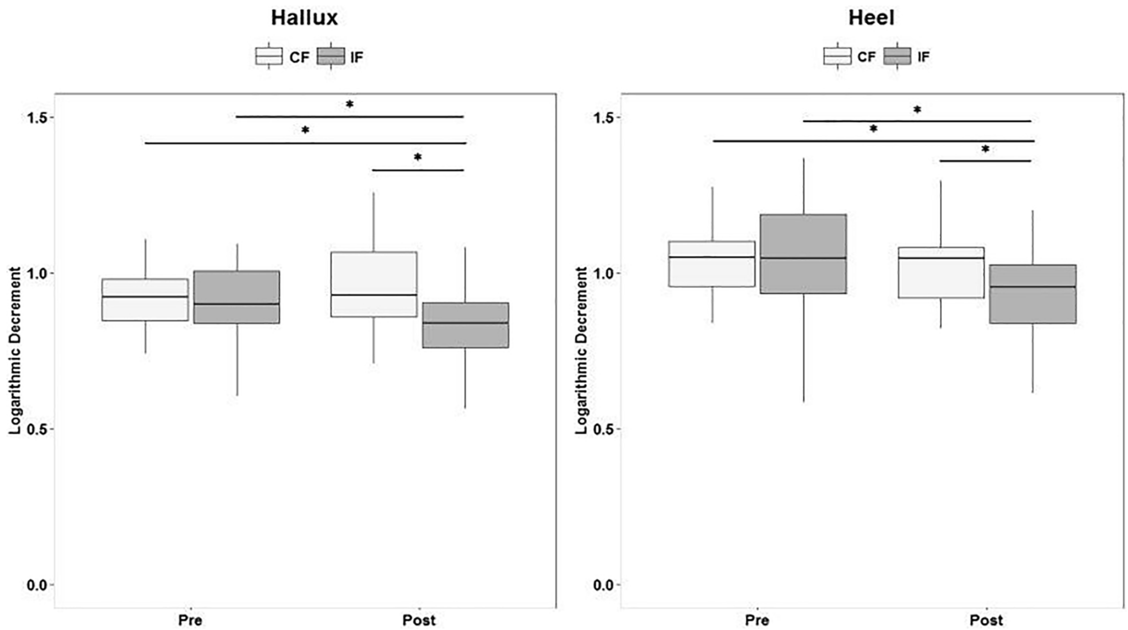

Fig. 1. Logarithmic decrement readings for the hallux (left) and heel (right). Boxplots show the control (CF) and intervention foot (IF) before (pre) and after (post) 45 min of water intervention. Significant differences: *p < 0.001, α = 0.0083. Statistical tests were performed based on log data (natural logarithm).

0.01 μm were shown to elicit neural activity in Vater-Pacini corpuscles [41]. Overall, water immersion did not induce significant changes in VPTs, thus rejecting our hypothesis. This finding contrasts another study, which showed that a fluid moisturizing oil-in-water emulsion improved the skin´s spatial discriminative ability [29]. They presume that peripheral, skin-related properties changed due to hydration. After hydration, the transfer of the stimulus toward tactile sensory receptors might be modified [29]. When indenting both prongs of the device into dry skin (flat, stiff surface), receptors located underneath and between the prongs were both stretched. Hence, there was less contrast between the receptor activity below and between the prongs, and subjects did not perceive them as individual items. The authors further assume that when indenting both prongs into hydrated skin (wavy, less stiff surface), only cutaneous receptors located directly underneath the prongs

Table 2
Mean ± SD of vibration perception thresholds (VPTs, μm) measured at the heel and hallux before (pre) and after (post) 45 min of water immersion. CF = Control Foot, IF = Intervention Foot. Statistical tests were performed based on log data (natural logarithm).

	CF (Mean ± SD)		IF (Mean ± SD)	
	Pre	Post	Pre	Post
Heel [μm]	2.0 ± 0.9	2.3 ± 1.1	1.9 ± 0.9	2.1 ± 1.0
Hallux [μm]	1.9 ± 2.1	1.9 ± 1.4	1.8 ± 1.8	1.6 ± 1.3

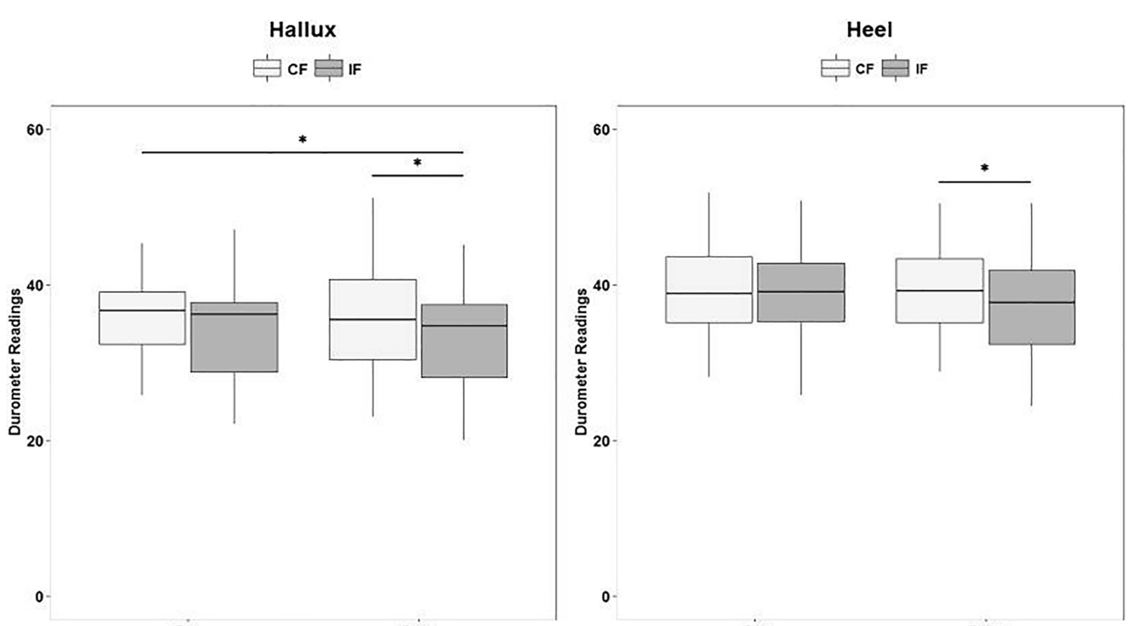

Fig. 2. Durometer readings for the hallux (left) and the heel (right). Boxplots show the control (CF) and intervention foot (IF) before (pre) and after (post) the water intervention. Significant differences: *p < 0.007, α = 0.0083. Statistical tests were performed based on log data (natural logarithm).

were activated. Receptors located between the prongs were not stretched due to the wavy, "softer" skin, hence, they were silent. This would result in a higher neuronal contrast and, therefore, in a high spatial two-point resolution [29]. However, we did not find significant changes in VPTs due to hydration. The reason for this might be that VPTs were measured using one single contactor at one location in our study. Hence, perception was less dependent on the neuronal contrast. Indeed, Lévêque and colleagues [29] found that receptors only moderately decreased their activity when comparing dry versus hydrated skin using a single contactor. It might be relevant, however, that those receptors were slowly adapting (SA) units. SA receptors are responsible for providing information while the prongs are in contact with the skin, exerting pressure. Surprisingly, the same study found a pronounced decrease in the receptor response after skin hydration when considering fast adapting (FA) receptors. This seems to contrast our findings, but may be explained by various differences. First, Lévêque et al. [29] did not specify the frequency of superficial stroking used to stimulate FA units. Hence, it remains unclear whether type FA I or FA II receptors were elicited. In a microneurographic study, 8–60 Hz was found to be the optimal stimulus to elicit plantar Meissner corpuscles (FA I) [24]. Second, they used readings from electrodes inserted into the afferent nerve fibers and not subjective methods as used in the current paper. Third, they tested at different anatomical locations (cheeks). Consequently, the thickness of the epidermis and stratum corneum (and hence the ability to take up water) was different compared to plantar aspects of the feet. The epidermis, especially the stratum corneum, normally contains little water (approx. 20%), but may easily and quickly take up water when the skin is immersed [30]. Consequently, this leads to an increase in the overall skin thickness [30,32]. We expected this to additionally dampen vibrations transmitted through the skin, resulting in decreased VPTs. This was not the case, which is an important outcome: 1) Water itself did not alter skin sensitivity as measured in our protocol. 2) Changes of mechanical properties also did not alter skin sensitivity. This is meaningful when examining the effects of warm/cold water on VPTs. Although only warm (adjusted to PTs) water was used in this study, we presume the results can be generalized. Hence, VPTs are not biased by water treatment of the skin. Assessing skin sensitivity is an important tool to identify various diseases. In addition, impaired skin sensitivity was found to predict ulcer formation [42].

In summary, previous studies using longer periods of skin wetting found detrimental developments of skin properties. We also found some detrimental developments, but after only 45 min of water exposure. However, this did not alter skin sensitivity. Our findings are relevant, especially for people with impaired skin recovery mechanisms. This may particularly affect skin areas exposed to increased pressure levels in persons who are bedridden. A limitation of our study is that we did not include ultrasound images, other test frequencies, or test sites.

4. Conclusions

We showed that short-term water exposure changed mechanical properties of the plantar skin, but not VPTs. Changes in mechanical properties were evident by overall decreases of the logarithmic decrement and decreases of durometer readings, constituting increased skin elasticity and softness. Similarly to previous studies examining long-term moisture exposure, our study also found softening effects, which may lead to similar detrimental effects. This may be relevant to prevent ulcer formation, especially in patients with impaired skin recovery mechanisms. Future studies should consider other measurements with respect to mechanical and sensitivity measures, as well as other anatomical locations to further investigate these processes.

Competing interests

All authors declare that there were no competing financial, professional, or personal interests that might have influenced the performance or presentation of the work described in this manuscript.

Author´s contribution

DS, AG and TM were involved in the study conception/design; data acquisition, analysis, and interpretation; drafting the article, and revising it critically for important content; and final approval of the final version.

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