WetTouch: Touching Ground in the Wearable Detection of Hand-Washing Using Capacitive Sensing

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***Abstract*—The detection of hand-washing is not only of interest since the emergence of the COVID-19 pandemic. Obsessive-compulsive disorder (OCD) often manifests itself in terms of hand-washing compulsions. Detecting these compulsions can potentially improve the effectiveness of treatments. Therapists can offer additional just-in-time mobile interventions, improved momentary assessment, and interactive exposure and reaction prevention (ERP) training. This, however, requires reliable and ambulatory detection of obsessive hand-washing. We present a novel technique which enables hand-washing detection by means of a wrist-worn, capacitive sensing device. It relies on the effect that touching running tap water yields a strong change in the capacitance between the wearer and the environment. The *WetTouch* system exploits this effect and we present first findings on the feasibility of such detection. For this, a set of seven pertinent activities with and without touching water was measured, and we found that hand-washing is clearly identifiable for two different subjects. The technique hence paves the path towards reliable and unobtrusive hand-washing detection in ambulatory applications with capacitive sensing.**

***Index Terms*—hand-washing, capacitive sensing, water, ground**

I. Introduction

Obsessive-compulsive disorder (OCD) is an impairing mental disorder that affects approximately 2.3% of all individuals at some point during their life [1], [2]. OCD is characterized by intrusive and unwanted thoughts, images, or impulses (obsessions) and repetitive, intentional rituals such as hand-washing (compulsions) performed in response to the obsession to reduce stress or anxiety [3], [4]. Washing and cleaning compulsions are the second most common form of OCD [5], [6], with more than half of diagnosed people (47.2 to 67.7 %) showing washing or cleaning compulsions [7]. Cognitive-behavioral therapy (CBT) with exposure and reaction prevention (ERP) is an effective treatment for OCD [8]–[10]. However, its efficacy depends on correctly following exposure exercises outside of therapy sessions, which often proves difficult because of the high anxiety associated with it [11].

With the ability to pin-point ritualised hand-washing, novel computer-assisted assessment, and therapy for OCD can be built. This has the potential to reduce health care costs and increase treatment efficacy for patients by providing real-time recommendations for adaptive exposure exercises in specific situations. However, the challenge is to answer whether compulsory hand-washing can be detected with wearable technology and distinguished from possibly confounding activities (e.g. non-obsessive hand-washing, eating, brushing teeth, …).

We describe a novel approach for hand-washing detection using capacitive sensing, which is the foundation for detecting compulsory hand-washing. As shown in Fig.1, touching water from the tap improves the capacitive coupling between body surface and earth ground, measured at the wrist. We exploit this effect for reliable hand-washing detection and show first experimental results on different experimental conditions. In this paper, we present the following contributions:

- A theory on the physical effect of touching water from the running tap on capacitive sensing applied at the wrist.
- The design of a wearable sensing device for measuring capacitance changes induced by touching the water jet.
- Two experiments confirming and substantiating this effect when washing hands at the tap of a conventional bathroom.

Our paper is structured as follows: We start with presenting the related work on hand-washing detection and capacitive sensing. Subsequently, we propose a physical model which serves as the basis of our research hypothesis. Based on that, we present our prototype and a first experimental evaluation. After the discussion of the results, we conclude with the main findings and a short outlook on future research.

II. Related Work

Wearable and mobile technology can facilitate OCD treatment, as demonstrated by two case studies on the treatment of OCD [12], [13]. However, these do not provide sufficient stimuli control techniques that could increase compliance with ERP. Reminders of helpful exercises [12] provide such control. Ideally these do not occur randomly but in response to the patient's current behaviour. Compulsive hand-washing is one such behaviour. When reminded just at the right time, affected individuals can instantly apply successful strategies in response to often automated, excessive compulsions. Compulsive hand-washing is done in a "stereotypical and even

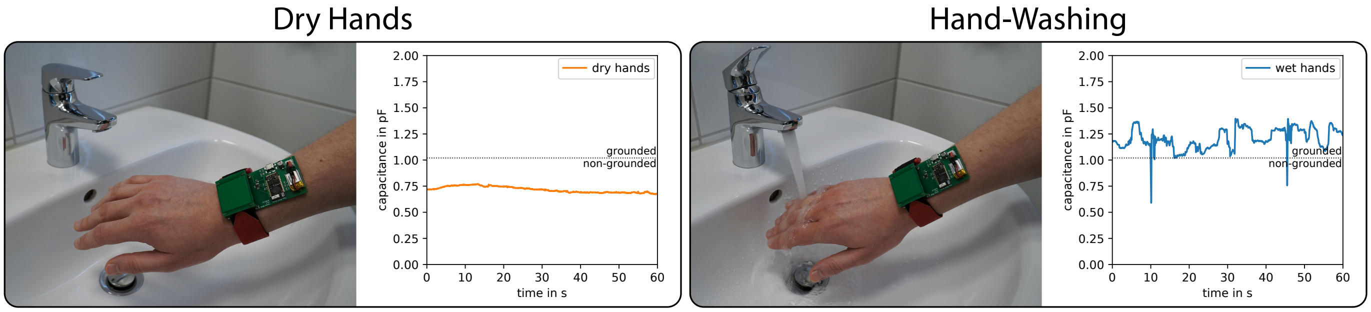

Fig. 1. The effect of changing capacitance measured with *WetTouch*. Illustrative time series of capacitance: When solely air-coupled to the environment, performing washing gestures (left) and when touching water, washing hands and hence water-coupled to the virtually infinite area of earth ground (right).

robotic" way [14]. Such repetitions of similar wrist movements is detectable by inertial motion sensors worn on the wrist, and distinguishable from other forms of hand movements, such as eating or brushing teeth. A Hidden Markov Model (HMM) on 6-axis inertial data was shown to have practical recognition rates for distinguishing steps of the washing procedure [15] recommended by the World Health Organisation (WHO). A more recent approach [16] reminds dementia patients about washing their hands. Another system [17], based on forearm electromyographical (EMG) measurements, was tested on the same WHO-recommended procedure with 17 participants. Both an Artificial Neural Network (ANN) and a HMM approach were shown to have practical recognition rates in distinguishing individual steps. Here, we are rather interested in the detection of compulsive hand-washing sessions, not the adherence to a specific procedure. The Harmony system [18] included Bluetooth beacons in the soap dispenser in addition to motion recognition, in order to improve the recognition of hand-washing. Instrumented dispensers [19] or sinks [20] for detecting hand-washing can be found in other works as well. While providing superior detection, these solutions can only be applied in controlled (instrumented) environments. This also applies to video-based detection solutions [21]. Detection with a water-sensitive finger ring allows for both personalized and non-instrumented detection [22]. The ring includes a coin-cell and fluid sensor, which allows for a runtime of about two weeks. Motivated by the COVID-19 pandemic, even commercial devices, such as the popular Apple Watch, have been given the feature of detecting hand-washing through sound and motion. We add a sensing principle to the aforementioned approaches, which allows for the reliable detection with a wrist-worn device based on capacitive sensing.

In general, capacitive sensing describes the detection of changes in electric fields which in turn result in the measurable variation of capacitance between conductive surfaces, denoted as electrodes. These variations might be caused by the modification or displacement of these measurement electrodes, or changes to the dielectric in between. Besides industrial sensors for fluid level, proximity, pressure, and humidity, capacitive sensing has become a very popular technique in human-computer interaction [23] for more than two decades, and has thoroughly been reviewed by Große-Puppendahl et al. [24]. In 1920, the Theremin [25] became a famous application in shape of a novel musical instrument. Today, capacitive touch sensors are common in vandalism-proof buttons, proximity sensors, and interactive touch displays of consumer devices like smartphones or tablets. The influence of water on their touch screens is usually unwelcome and mitigated [26]. With Touché [27], a system on swept-frequency capacitive sensing has been presented, which uses electrodes integrated in devices to interact with. In a particular setting, mounted at the bottom of a tank, the setup enables to detect different gestures in and the interaction with liquids, such as water, demonstrating the influence of water on the capacitive sensing principle. In contrast to that concept, we present a system in which a pair of electrodes is worn at the skin instead of being attached to specific objects or mounted in the environment.

III. Sensing Principle

Tap Water: Water is regularly expected to conduct electric current perfectly, but pure H_2O is actually an excellent insulator ($\rho \approx 18.2\,\mathrm{M\Omega\,cm}$ at $25\,^\circ\mathrm{C}$). However, dissolved substances and salts, such as sodium chloride (NaCl), bring in ionic compounds which free ions increase electric conductivity. Nevertheless, the specific electrical resistance ρ of tap water is still high, in the order of 0.2 to $20\,\mathrm{k\Omega\,cm}$. In contrast to air ($\varepsilon_r \approx 1$), water shows, however, a comparably large relative permittivity ε_r of about 80. The preferred quality of water to wash the hands is drinking water. According to the WHO, about $87\,\%$ of the global population have access to drinking water from "improved sources" while $54\,\%$ have a piped supply [28]. Early pipelines were made from cast iron or even toxic lead, and hence conductive (ρ in the order of $\mathrm{\mu\Omega\,cm}$). They have often been utilized to ensure the potential equalization throughout a building, since they were leading into the mass of earth and hence connected to ground. Today, besides the remaining old facilities, new pipelines are now and then made from costly copper but more often made from cheap insulating plastics. Hence, potential equalization cannot be implemented and guaranteed through the supply pipes anymore. Nevertheless, all conductive connections leading into buildings (service entrance), as well as all metallic facilities inside, must be bonded to ground to avoid electric shocks [29].

Earth Ground: Instead of using the water pipes, nowadays, a ground wire is driven into the soil next to buildings, to ensure the interior being connected to the earth's virtual zero potential, denoted as earth ground. Along with its importance in building systems, it generally serves as a return path 'all around the world' and a common neutral reference potential, providing a virtually infinite reservoir of electrical charge and allowing for the neutralization of charged objects. Every object without a conductive connection to a certain fixed potential is denoted as floating. Although providing a local circuit ground, usually associated with the negative terminal of the battery, a wearable electronic device, such as our prototype, is floating without any conductive connection to the earth ground.

Capacitive Coupling: According to [29], a capacitance is established between any conductive surfaces and their different charging results in an electric field. The capacitance C of an ideal parallel plate capacitor is given in (1) through two facing electrodes with an area A and a distance d, separated by a dielectric with the absolute permittivity ε_0 of free space in vacuum ($8.854 \times 10^{-12}\,\mathrm{F\,m^{-1}}$) and a relative permittivity ε_r. While air has $\varepsilon_r \approx 1$, any different material has $\varepsilon_r > 1$.

$$C \;=\; \varepsilon_0\,\varepsilon_r\,\frac{A}{d} \tag{1}$$

All objects couple to the environment, basically to the mass of earth and its earth ground potential. Likewise the human body forms natural capacitances in the order of several hundred pF [23], [24], [30]. Due to the insulating dielectric between the electrodes, no direct current (DC) can flow from one side to the other. The application of a changing potential difference, and hence a time-varying electric field, induces, however, an alternating current (AC), denoted as displacement current $\vec{i_d}$. For such an alternating signal at frequency f, the ideal capacitance C results in the imaginary impedance Z_C, given in (2), with the angular frequency $\omega = 2\pi f$. For an increasing f the impedance Z_C hence decreases and with $\lim_{f\to\infty} Z_C = 0$ it virtually resembles a short circuit.

$$Z_C \;=\; \frac{1}{j\omega C} \tag{2}$$

Physical Model: Based on the previously introduced fundamentals, we developed a physical model that is illustrated in Fig. 2. We posit that the excitation electrode at *EXC* strongly couples to the adjacent skin. In the resulting transmit mode [23], [24], it virtually enlarges to the entire body surface and hence modulates the electric field of the human body. Meanwhile the floating sensing electrode at *CIN* couples to diverse surfaces: Directly to the counterpart electrode at *EXC*, but also to the body surface modulated through *EXC* and the environment, earth ground with its virtually infinite area. Once the water jet is touched, a new branch bypasses the path through air with a larger permittivity and hence a stronger electric field. The respective change of the capacitance C_x is measured at the *WetTouch* prototype. The equivalent circuit from its two-port perspective is provided in Fig. 3. Every facing conductive surfaces establish a capacitance C, represented by an imaginary impedance Z, as defined previously in (2).

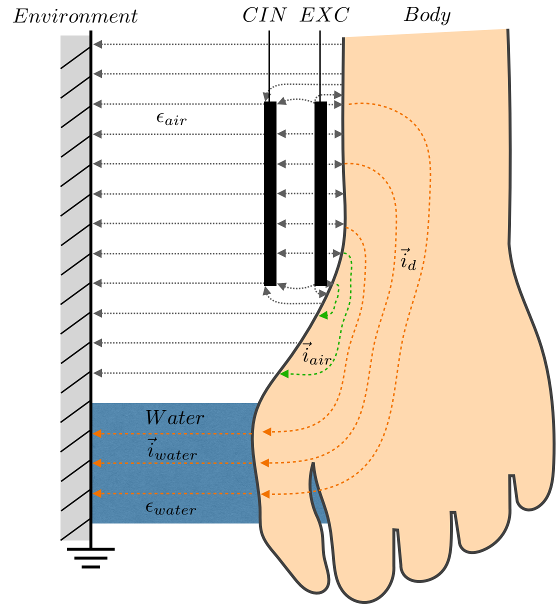

Fig. 2. Illustration of the proposed sensing principle. By touching the water jet, the coupling to earth ground is improved through its virtually infinite area, which in turn is measurable with the wrist-worn *WetTouch* prototype.

Following the high potential from *EXC* via the floating *CIN* to earth ground *GND*, those are exemplified as follows:

- Z_{ec}: The facing electrodes *EXC* with A_e and *CIN* with A_c couple directly but weakly due to the air gap d_{ec} in between. For $A_e = A_c = 3 \times 3\,\mathrm{cm}^2$ and $d_{ec} = 1\,\mathrm{cm}$, the intrinsic capacitance C_{ec} is in the order of $0.797\,\mathrm{pF}$.
- Z_{eb}: Due to $\lim_{d\to 0} Z_{eb} \to 0$, *EXC* strongly couples to the body surface A_b (transmit mode [23], [24]), which virtually enlarges *EXC*'s surface to the entire body surface $A_e := A_b$.
- Z_{bc}: The body directly couples to *CIN* with $A_c < A_b$.
- Z_{cg}: *CIN* weakly couples to *GND*, the environment with a large surface A_{gnd} but a comparably small distance d_{gnd}.
- $Z_{bg,air}$: The body A_b also couples to *GND* through air.
- $Z_{bg,wat}$: If available, the body A_b couples to *GND* A_{gnd} via the water jet with $\epsilon_{r,wat} > \epsilon_{r,air}$, hence bypassing $Z_{bg,air}$.

The equivalent impedance Z_x of the sensing two-port is given in (3). The water $Z_{bg,wat}$ hence bypasses the air path $Z_{bg,air}$ and increases the measurable total displacement current $\vec{i_x}$.

$$Z_x \;=\; (Z_{ec} \;\|\; Z_{bc}) \;\|\; (Z_{cg} + (Z_{bg,air} \,\|\, Z_{bg,wat})) \tag{3}$$

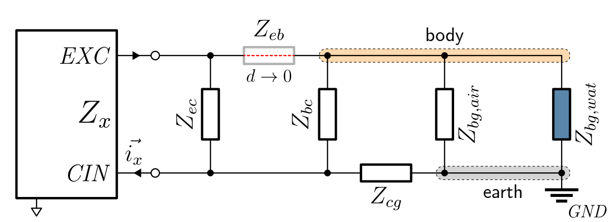

Fig. 3. Equivalent circuit of the sensing impedance Z_x, a two-port from the perspective of the floating wearable device, derived from the physical model. Due to $d \to 0$, the contact impedance Z_{eb} disappears and virtually enlarges *EXC*'s electrode to the entire body surface (transmit mode [23], [24]).

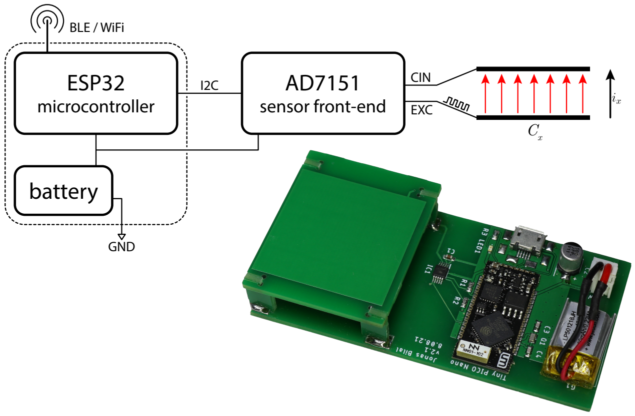

Fig. 4. Block diagram (top) and the assembled *WetTouch* prototype (bottom): The two $3 \times 3\,\mathrm{cm}^2$ measurement electrodes with $1\,\mathrm{cm}$ air gap, the *AD7151* capacitance-to-digital converter (CDC), the *ESP32* microcontroller with wireless Bluetooth / Wi-Fi connectivity, and a rechargeable battery. Excitation electrode (*EXC*) and floating sensing electrode (*CIN*) measure the capacitance C_x by means of the transferred charges, the displacement current $\vec{i_x}$ respectively.

IV. Implementation

To confirm the physical model, a wearable prototype has been developed to perform basic experiments. It enables to sensitively measure the capacitance between two electrodes: An excitation electrode (*EXC*) to couple to the wearer's body and a floating sensing electrode (*CIN*) to couple to the earth.

Wearable Sensing Device: The *WetTouch* prototype, presented in Fig. 4, has two electrodes, arranged one above the other with an air gap. Capacitance changes are measured by an *AD7151* capacitance-to-digital converter (CDC) and then provided to an *ESP32* microcontroller that either forwards the recordings via Bluetooth / Wi-Fi or stores them locally. The battery-powered device can be attached to limbs through a hook-and-loop tape and is designed to be comfortably worn at the lower arm, almost like a traditional wristwatch.

Electrode Setup: The 'sandwich' electrode setup has been adapted from previous research [31] and is made from standard *FR4* PCB substrate ($1.55\,\mathrm{mm}$) with laminated copper foil ($35\,\mu\mathrm{m}$). Both electrodes measure an area A of $3 \times 3\,\mathrm{cm}^2$ and are stacked with an air gap d of $1\,\mathrm{cm}$. This forms a parallel plate capacitor which ideal intrinsic capacitance C_{ec} is $0.797\,\mathrm{pF}$, given through (1). To achieve the intended poor coupling of the electrodes, neither the circuitry nor any filling ought to be placed between the electrodes. Any material other than air ($\varepsilon_r \approx 1$) would result in a larger $\varepsilon_r > 1$, improve coupling, and hence increase C_{ec}. The electrodes' substrate as well as the four spacers at the corners are, however, required to keep the plates in place, and inevitably increase the capacitance slightly. A larger d would reduce coupling, but the dimensions are limited through the device's obtrusiveness. A solder mask is applied to prevent direct skin contact.

Capacitance-to-Digital Converter: There exist diverse techniques [32] to measure the tiny capacitance between conductive structures. Because the effect of hand-washing on the inter-electrode capacitance is expected to be rather weak, a sensitive front-end is required. We decided for the *AD7151* [33], an ultra-low power ($70\,\mu\mathrm{A}$ at $3.3\,\mathrm{V}$) capacitance-to-digital converter (CDC) which enables to directly obtain a digitized value. It is designed for the single-channel measurement of floating capacities at the ranges 0 to 0.5, 1.0, 2.0, or $4.0\,\mathrm{pF}$ with $12\,\mathrm{bit}$ resolution, at a maximum sensitivity of $1\,\mathrm{fF}$ respectively. We decided for the range of $2\,\mathrm{pF}$, resulting in a sensitivity of $1.6\,\mathrm{fF}$. To capture the sensor's C_x, the integrated circuit measures the charge transfer between its two pins *EXC* and *CIN*. It applies a square wave to *EXC*, with limited slew rate and an excitation frequency of $16\,\mathrm{kHz}$, while the opposite *CIN* meters the charge using a Σ-Δ modulator. A subsequent digital filter averages the measurements while the conversion time is $10\,\mathrm{ms}$. The microcontroller takes the measurement every $50\,\mathrm{ms}$, resulting in a sampling rate of $20\,\mathrm{Hz}$.

V. Experiments and Evaluation

Since our goal is to distinguish hand-washing from other activities, we tested whether this is possible with the change of capacitance through touching the jet from the water tap. We hypothesize that the capacitance of the wrist-worn electrode pair changes due to the adjacent body coupling through the water jet and via the supply pipes to earth ground. If this effect causes a measurable difference in the capacitive reading, hand-washing should be distinguishable from other activities.

Experiment 1: To show whether such an effect exists, we took measurements with different conditions and activities. A single subject (S1: male, $25\,\mathrm{yr.}$, $177\,\mathrm{cm}$, $70\,\mathrm{kg}$) wore the device performing the following: $\langle 1 \rangle$ grounding himself through the mains' neutral wire, $\langle 2 \rangle$ washing gestures with dry hands, $\langle 3 \rangle$ hand-washing with water running from a tap, $\langle 4 \rangle$ washing gestures with wet hands in a wash pan, $\langle 5 \rangle$ arbitrary gestures, $\langle 6 \rangle$ contacting one foot with running tap water, and $\langle 7 \rangle$ brushing teeth with a traditional toothbrush. The histograms of the CDC readings are shown together with the respective activity in Fig. 5 and 6. The overlapping conditions $\langle 1, 3, 6 \rangle$ confirm the aforementioned hypothesis. The body is coupled to earth ground in those *grounded* conditions, either through direct skin contact or the water jet. In contrast, the *non-grounded* conditions $\langle 2, 4, 5, 7 \rangle$ do not overlap with the *grounded* ones, even for $\langle 5 \rangle$. The close proximity of the wearable sensor to the subject's head in $\langle 7 \rangle$ might cause the relatively large capacitance while the other activities are performed with stretched arms and hence the sensor farther away from the body. Instead of the contacted water, the body then acts as a large, proximate ground plane. Although the hands get in contact with water, activity $\langle 4 \rangle$ lies in the *non-grounded* part of the measurements, confirming that the connection to earth ground is required to achieve the desired capacitance measure. This means that hand-washing activities can only be detected when the water is running through a ground-bonded tap or a pipeline originated in the mass of earth. For S1, hand-washing and simultaneously touching the water running from a tap $\langle 3 \rangle$ yields an average capacitance of $1.205 \pm 0.099\,\mathrm{pF}$ and forms a distinct cluster that may allow to distinguish hand-washing from other activities such as arbitrary motion $\langle 5 \rangle$ with an average capacitance of $0.793 \pm 0.325\,\mathrm{pF}$. To enable the detection of grounding in a first approach, a simple threshold is set to the midpoint between the means of *non-grounded* and *grounded* classes at 1.011 pF. Further distinction of hand-washing from other activities with a grounded body is probably possible since additional motion leads to a wider spread of the measurements, as apparent from the clusters ⟨1⟩ versus ⟨3⟩.

Experiment 2: In order to proof the reproducibility of the observed effect, the conditions ⟨2⟩ washing gestures with dry hands and ⟨3⟩ hand-washing with water running from a tap have been repeated with two subjects, five times and for 30 s each. S1 is male, 25 years, 177 cm, 70 kg and S2 is male, 61 years, 170 cm, 90 kg. The histogram in Fig. 7 shows a similar distribution as Fig. 5 from the first experiment. The clusters of ⟨2⟩ and ⟨3⟩ are clearly separated. However, ⟨2⟩ is rather scattered while ⟨3⟩ appears evenly spread.

We argue that hand-washing is indeed detectable and distinguishable from other activities, but did not yet apply the system to a larger variety of users and sinks in different environments. When considering the results, it is visible that the effect of grounding the body has the largest influence, which means that different body types, composition, and height will only have a limited influence. Furthermore, the sensing mechanism is based on the change in capacitance, caused by the water jet which bypasses the air path and hence improves the coupling between the human body and earth ground. On the one hand, this feature limits the possible applications of the sensing principle to water taps which supply pipes are originated in the mass of earth or even directly bonded to earth ground, commonly found in building installations. On the other hand, the body is required to be properly insulated from the earth ground. For the application that motivated this work, i.e. detecting obsessive hand-washing, this situation can be safely assumed. Hand-washing is not the only activity where the body comes into contact with water and some confounding activities, e.g. dish-washing with a running tap, will probably show quite similar measurements. These could be distinguishable by more sophisticated analyses, for example by considering the overall water contact time or other time-dependent characteristics. The swept-frequency capacitive sensing method, presented in Touché [27], might also be an option to improve the classification by analysing the frequency-dependent coupling instead of measuring at a constant excitation frequency of 16 kHz. Inertial Measurement Unit (IMU) sensors can also be used in conjunction with the presented approach to remove possible confounding situations.

VI. Conclusion

We have presented a novel technique for the detection of hand-washing, based on capacitive sensing, which uses the effect of grounding through touching water from a running tap. We developed a physical model which has been substantiated in two initial experiments with recordings from two subjects. The results are promising and show that the proposed method allows to distinguish hand-washing from other activities. In our experiments, the measured capacitance during hand-washing is distributed around 1.152 ± 0.106 pF and hence separates clearly from washing gestures with dry hands around 0.671 ± 0.065 pF and other activities such as arbitrary gestures around 0.793 ± 0.325 pF (S1). A simple threshold on a running average is therefore sufficient to detect if the body is grounded through water while an additional analysis of the standard deviation allows to identify hand-washing. Obsessive hand-washing is then detected by the duration and frequency of the hand-washing sessions.

Next, we are going to design an improved and miniaturized prototype which will enable to run a larger study with more subjects and buildings, a larger diversity of water taps and supply pipes respectively. Instead of the floating 'sandwich' electrode setup, the local circuit ground will serve as a stable reference, present throughout the entire PCB's ground plane. Further, an active shield might enable to separate the sensing electrode from the circuit ground to supersede the required but impractical air gap between the electrodes. We envision our system as an additional tool for objectively detecting obsessive hand-washing, to facilitate individual therapy sessions.

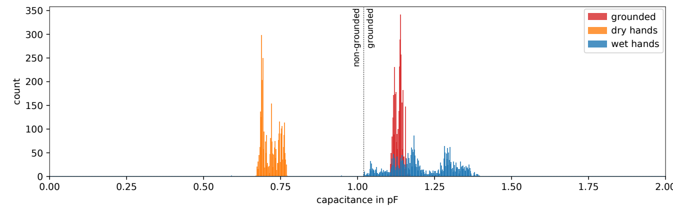

Fig. 5. Distribution of measurements from a single subject (S1): ⟨1⟩ grounded body (red, 1.133 ± 0.013 pF), ⟨2⟩ washing gestures with dry hands (orange, 0.718 ± 0.028 pF), and ⟨3⟩ hand-washing with water running from a tap (blue, 1.205 ± 0.099 pF). Separation line and simple threshold between the classes *non-grounded* and *grounded* (black, 1.011 pF).

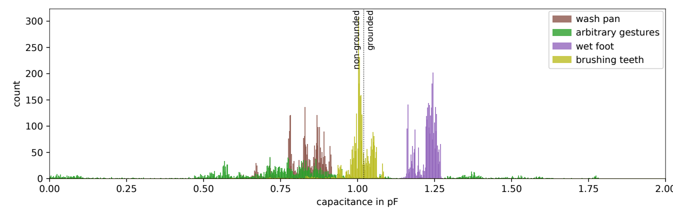

Fig. 6. Distribution of measurements from a single subject (S1): ⟨4⟩ washing gestures with wet hands in a wash pan (brown, 0.823 ± 0.065 pF), ⟨5⟩ performing arbitrary gestures (green, 0.793 ± 0.325 pF), ⟨6⟩ contacting one foot with running tap water (violet, 1.225 ± 0.031 pF), ⟨7⟩ and brushing teeth with a traditional toothbrush (light green, 1.007 ± 0.047 pF).

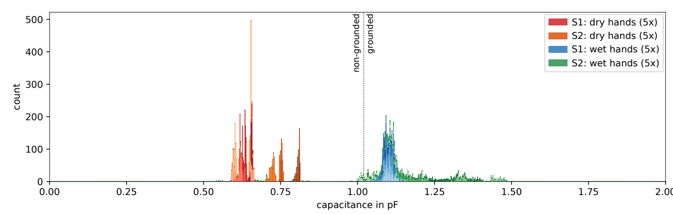

Fig. 7. Distribution of additional measurements from two different subjects: S1 (male, 25 yr., 177 cm, 70 kg) and S2 (male, 61 yr., 170 cm, 90 kg). Dry hands ⟨2⟩: S1 (5×30 s, red, 0.635 ± 0.026 pF) and S2 (5×30 s, orange, 0.707 ± 0.073 pF). Wet hands ⟨3⟩: S1 (5×30 s, blue, 1.099 ± 0.018 pF) and S2 (5×30 s, green, 1.205 ± 0.128 pF). Five 30 s measurements per subject and class, 10 min recordings in total. In-class averages for ⟨2⟩ dry hands (0.671 ± 0.065 pF) and ⟨3⟩ wet hands (1.152 ± 0.106 pF).

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