Developing and testing a portable device for tracking small deviations in the hydration levels of a human body

by
Saloni Bedi

Bachelor in Design (2017),
MAEER's MIT Institute of Design, India

Submitted to the Integrated Design and Management Program
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering and Management
at the
Massachusetts Institute of Technology

June 2023

Authored by: **Saloni Bedi**
Integrated Design and Management Program
May 22, 2023

Certified By: **Martha Gray**
Professor of Electrical Engineering & Computer Science
Thesis Supervisor

Accepted By: **Antonio Hu**
Director of Integrated Design & Management Program

Developing and testing a portable device for tracking small deviations in the hydration levels of a human body

by
Saloni Bedi

Submitted to the **Integrated Design and Management Program**
on **22nd May 2023**
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Engineering and Management

Abstract

Maintaining proper hydration is widely recognized as essential for overall health, yet dehydration remains a prevalent issue, particularly among vulnerable populations such as the very young and elderly, and can contribute to increased morbidity and mortality rates. There have been numerous endeavors in both academia and industry to develop non-invasive methods for monitoring hydration status, specifically in non-clinical settings. However, a practical and reliable solution for routine hydration measurements is still lacking.

To address this critical need, the hydration team at MIT has been actively working on the development of a non-invasive sensor to bridge the gap in hydration monitoring. This thesis focuses on the development of a wearable setup for the existing technology, enabling human studies to be conducted with individuals by comfortably integrating the hydration sensor into their daily routines for study periods of 24 hours and longer. The primary objective of the human studies is to investigate whether the sensor readings obtained during prolonged periods of dehydration can be distinguished from those obtained during normal (euhydrated) activities.

Throughout the course of this research, a comprehensive wearable setup was meticulously developed. Human studies were conducted in two distinct cohorts, namely Euhydration and Dehydration, where participants wore the wearable setup to capture hydration data. This allowed for the analysis of hydration trends and would help with a comparative assessment of sensor readings under different conditions.

The results obtained and the data analysis facilitates the evaluation of the wearable setup's efficacy and reliability in monitoring hydration status during prolonged periods of dehydration. Furthermore, the findings contribute to the advancement of hydration monitoring by shedding light on the potential of distinguishing between hydration states using the developed wearable setup.

Thesis Supervisor: Martha Gray
Title: Professor of Electrical Engineering & Computer Science

Acknowledgment

My thesis journey has been filled with lots of ambiguity, exploring, learning new skills, endless questions, and many hours of work. Looking back, I can see how much I have grown over the course of the last one and a half years and I have a lot of people to be grateful to!

First and foremost, I would like to extend my heartfelt appreciation to my advisor, Prof. Martha Gray. Your unwavering support, patience, and guidance have been instrumental in getting this research to where it is at this point. Your insightful feedback and encouragement have continuously motivated me to strive to do better and to keep going. I am truly grateful for the opportunity to work under your mentorship.

I would also like to extend my gratitude to the members of the research project, Ian, and Quang. Ian's problem-solving skills, immense knowledge in the area, and constructive feedback have been invaluable for me to learn and grow. Quang's dedication to the project and willingness to share his knowledge and ideas have been of tremendous help to understand and work on this research. I am grateful for all that I have learnt and experienced through this research.

I would also like to acknowledge the participants who volunteered their time and efforts to be a part of this study. Their participation and cooperation have been essential in collecting the necessary data and insights, without which this research would not have been possible.

I am also indebted to the Integrated Design and Management program and the team at IDM for providing me with a conducive learning environment and the opportunity to pursue my academic aspirations. The program's interdisciplinary approach and emphasis on innovation and design thinking have broadened my perspective and equipped me with invaluable skills for this research endeavor.

I also want to thank my friends and family whose support I emotionally leaned on throughout the last two years. It would not have been possible to get to this stage in my life without them cheering me on throughout the highs and lows of the past two years of my master's education. I could not have fought the many internal and external battles through this journey without Sarad (and his grit), Akanksha (and her wisdom), Kanal (and her infectious spirit), Chandu (and her can-do attitude), Chochu (and her passion for life), and Kanika (and her unwavering support).

MIT has changed my life and I will always remember it for being the place where you can work towards bringing your dreams to life, and where you are always surrounded by the most hardworking beavers who have the will to change the world for the better. I hope to always remember the lessons of being bright-eyed, curious, collaborative, and relentless that MIT has taught me!

Table of Contents

List of Figures

List of Tables

Chapter 1: Background

Introduction:

Water is the elixir of life, an indispensable component that sustains our very existence. Its significance cannot be overstated, as it forms the largest proportion of the human body, accounting for approximately 50-70% of adult body mass. This ratio, influenced by factors like age, sex, and body fat composition, highlights the fundamental role that water plays in our physiology. [1] There has been significant research regarding the importance of staying hydrated and the recommendations for staying hydrated are well-known too.

Dehydration happens when the body experiences a net loss of fluids, surpassing the amount of fluid it receives. Although there is a gap in the support in medical literature, dehydration has been reported to occur in 17% to 28% of older adults in the United States[2]. This can occur in people of all ages, but it is particularly common in children, older adults, and athletes. It can be caused by various factors, including excessive sweating, vomiting, diarrhea, and inadequate fluid intake. Low levels of hydration can have various kinds of health effects: mild dehydration can result in headache, tiredness, and thirst while severe cases could lead to fever, rapid heart rate, increased respiration, decrease in cognitive performance, and even unconsciousness in some cases. [3] [4]

Dehydration has been found to be a frequent cause of hospital admissions and can be a cause of morbidity and mortality along with being a reason for complications of many medical conditions. If left untreated, dehydration can cause serious health complications such as kidney failure, seizures, and in some cases death. Symptoms of dehydration include thirst, dry mouth and throat, dark urine, fatigue, dizziness, confusion, and rapid heartbeat. One of the symptoms is thirst, thirst forms the body's means for self-monitoring for dehydration, but thirst can easily be ignored or overshadowed, and in the case of older adults in care, a care provider cannot directly monitor the subject's thirst.

Some of the treatments involve replacing lost fluids and electrolytes through drinking water, oral rehydration therapy (ORT), or intravenous fluids in severe cases. Its common knowledge that proper hydration can be maintained by regularly drinking water and other fluids, especially during physical activity or in hot weather. Even though dehydration is easy to treat

---

[1] Lacey et al., "A Multidisciplinary Consensus on Dehydration."

[2] Weinberg and Minaker, "Dehydration. Evaluation and Management in Older Adults. Council on Scientific Affairs, American Medical Association."

[3] Shaheen et al., "Public Knowledge of Dehydration and Fluid Intake Practices."

[4] Liska et al., "Narrative Review of Hydration and Selected Health Outcomes in the General Population."

and prevent if steps are taken for prevention, but in the absence of indicators like thirst it can also be overdiagnosed, which may lead to the misdiagnosis of a patient's real illness[5]. It has been noted that non-invasive measurement methods can close the loop by providing an indication of changes in hydration status can be crucial to provide important guiding information to prompt treatment before an individual becomes severely dehydrated.

Overview of Dehydration

Dehydration refers to total body water (TBW) deficit and can be a result of any process that could lead to a negative water balance i.e. water intake is less than water loss. Water is distributed across many body compartments and is also not uniformly distributed among different organ systems, for example, fat tissue, bone, and muscles have approximately 15%, 30%, and 80% water respectively. Because of these conditions, in the case of dehydration, the water loss is generally not distributed in a uniform manner across these body compartments and it becomes crucial to consider these regions or compartments while evaluating the measures of dehydration. In healthy adults with normal Body Mass Index (BMI), water accounts for about 60% of body weight.[6] Even a slight loss of 3% of body weight due to water depletion can result in dehydration. When the body experiences a decrease in water intake without replenishment, it can lead to difficulties in memory and attention. This highlights the negative impact of even a modest loss of body mass on cognitive functions.[7] [8] Studies have reported that dehydration by 1–2% could impair cognitive performance and impact psychomotor and memory skills. A 4% fluid deficit leads to a decline in performance, resulting in symptoms such as headaches, irritability, and sleepiness in children. Additionally, it causes an elevation in respiratory rate and an increase in body temperature.[9] Dehydration can also impair muscle endurance and decrease muscle strength. [10] Fluid depletion of more than 8% could also cause death. Healthcare providers are generally aware of the ideal fluid balance states, dehydration, and euhydration but public awareness of some symptoms of dehydration has shown to be lacking. [11]

---

[5] Taylor and Jones, "Adult Dehydration."
[6] "Recognizing_the_face_of_dehydration.10.Pdf."
[7] "Recognizing_the_face_of_dehydration.10.Pdf."
[8] Benton et al., "Minor Degree of Hypohydration Adversely Influences Cognition."
[9] Benton and Young, "Do Small Differences in Hydration Status Affect Mood and Mental Performance?"
[10] Savoie et al., "Effect of Hypohydration on Muscle Endurance, Strength, Anaerobic Power and Capacity and Vertical Jumping Ability."
[11] Shaheen et al., "Public Knowledge of Dehydration and Fluid Intake Practices."

Types Of Dehydration

More expansive definitions of dehydration are outlined based on the physiological effects on the extracellular compartment: hypotonic, isotonic, or hypertonic dehydration. Isotonic dehydration refers to a deficiency of water that is accompanied by a proportional loss of salts. This type of dehydration can occur with conditions such as diuretic usage or secretory diarrhea. On the other hand, hypertonic dehydration is characterized by an uncompensated water deficit, primarily involving the loss of pure water. This type of dehydration commonly arises from inadequate fluid intake or excessive sweating.[12]

Most of the literature does not differentiate between the various forms of dehydration and in this thesis, the term dehydration is used to mean loss of body water by any means.

Symptoms of Dehydration

Thirst is a prominent indicator of dehydration, yet it can be disregarded or overlooked, making it difficult for a caregiver to directly monitor an individual's level of thirst. The National Health Service (NHS) identifies several symptoms of dehydration in both adults and children. These symptoms include experiencing thirst, producing dark yellow and strong-smelling urine, urinating less frequently than usual, feeling dizzy or lightheaded, experiencing fatigue, having a dry mouth, lips, and tongue, as well as having sunken eyes. These signs serve as important cues for recognizing and assessing dehydration in individuals. Monitoring and addressing these symptoms are crucial in preventing and managing dehydration-related complications.[13]

There are numerous symptoms like the ones mentioned above and others covered in literature like fatigue, confusion, palpitations, nausea, lethargy. But these symptoms of early dehydration can be quite nonspecific and could be confused for a variety of other conditions. Individuals cannot judge the presence or severity of dehydration in the absence of a readily available method, tool, or device to measure a person’s dehydration status in a non-clinical setting.

Treating Dehydration

There exist simple techniques to address mild to moderate dehydration, such as increasing fluid intake through oral rehydration therapy (ORT), a clinical method. ORT is suitable for mild

[12]Lacey et al., “A Multidisciplinary Consensus on Dehydration.”
[13] NHS, “Dehydration.”

(3 to 5%) to moderate (6 to 9%) dehydration as it allows the body's natural regulatory systems to restore euhydration by adjusting the excretion of salt and water through the kidneys. In cases of severe dehydration, intravenous (IV) administration is a commonly employed method for rapid rehydration. The administration of IV fluids necessitates trained personnel to determine the composition and rate of fluid administration, as well as to monitor the body's response to maintain a proper fluid balance. [14]

Detection of Dehydration

Unfortunately, there is currently a lack of reliable measurement technologies to assess hydration status, particularly in a nonclinical setting. The best available tests include serum osmolality (requiring a blood draw and clinical lab) and weight loss (requiring a baseline and subject to confounding factors). A recent review of symptoms, signs and minimally invasive tests to identify the occurence of dehydration in older adults made a conclusion that commonly used signs and symptoms for dehydration lack even the basic levels of diagnostic accuracy in older adults. [15]

To detect the early stages of dehydration, measurements and non- invasive assessment to detect mild to moderate dehydration can provide crucial information to guide ORT in a timely manner.

Populations affected by dehydration

Older adults: Dehydration in the elderly is a common and critical issue, and we don't have the tools to solve it. As people age, there is a decrease in body water content, a decline in thirst and other mechanisms that regulate fluid balance, and an increase in both mental and physical fragility. In elderly care homes, the issue is magnified and nurses are tasked with the task of ensuring residents stay hydrated; a challenge given that there is currently no easy and reliable method for nurses to assess hydration. Today's nurses are forced to carefully monitor intake, output, and body weight, each of which is prone to inaccuracy and can correlate poorly with actual body hydration. As a result dehydration frequently occurs and can cause acute complications, leading to hospitalization—a marker of poor prognosis in this

[14] Gray, Birkenfeld, and Butterworth, "Noninvasive Monitoring to Detect Dehydration."
[15] Bunn and Hooper, "Signs and Symptoms of Low-Intake Dehydration Do Not Work in Older Care Home Residents—DRIE Diagnostic Accuracy Study."

population that heavily impacts the quality of life. Dehydration is associated with poor health outcomes and increased hospital admissions.[16]

In older individuals, the signs and symptoms of dehydration and decreased volume can be subtle, misleading, or sometimes even unnoticeable. Thus, different clinical changes must be evaluated in older patients, specifically targeting function and oral fluid intake.

Children: Dehydration is a significant contributor to illness and death among infants and young children globally. Approximately 760,000 children are affected by diarrheal diseases each year, resulting in dehydration. The primary cause of dehydration in children is typically acute gastroenteritis. Infants and young children are especially vulnerable to diarrheal diseases and dehydration due to factors such as their higher metabolic rate, inability to effectively communicate their hydration needs or replenish fluids themselves, and increased loss of fluids through insensible means. Other causes of dehydration may be the result of other disease processes resulting in fluid loss which include: diabetic ketoacidosis (DKA), diabetes insipidus, burns, excessive sweating, and third spacing. Dehydration may also be the result of decreased intake along with ongoing losses. In addition to total body water losses, electrolyte abnormalities may exist. Infants and children have higher metabolic needs and that make them more susceptible to dehydration.[17]

Performance sports: Dehydration can affect how well humans perform physically, and it's a complex issue. When an individual becomes dehydrated, changes occur in the body that can impact how it works. Most studies show that losing 2% or more of body weight due to dehydration can hurt endurance and exercise performance, and it can also have a smaller negative effect on the individual's strength and power. It doesn't matter if individuals start exercising already dehydrated or if they become dehydrated during exercise. [18]

Current Assessment Techniques

The clinical method to assess dehydration is on the basis of history, signs, and symptoms with history being key as signs and symptoms can be relatively insensitive in the occurrence of mild and moderate dehydration. One of the main challenges for most of the measures is that the values can widely change amongst individuals, which makes a single point measurement difficult to measure. The current assessment techniques are briefly outlined below:

---

[16] Bunn et al., "Effectiveness of External Factors to Reduce Dehydration Risk in Older People Living in Residential Care: A Systematic Review."

[17] Vega and Avva, "Pediatric Dehydration."

[18] Cheuvront and Kenefick, "Dehydration: Physiology, Assessment, and Performance Effects."

- Body Mass changes and Isotope Dilution: In the absence of any gold standard for measuring Hydration status, the closest thing is Body Mass Loss. With controlled protocols, the standard is widely considered to be a body mass loss (BML) of more than 2%: at 2% loss, there is a 90% likelihood of dehydration. [19] This Body mass loss can represent changes in total body water as long as the intake is restricted or controlled and is tracked over a short period so muscle and fat mass hasn't changed. This method lacks an indication of the compartment from which the fluid is lost or gained which is where Isotope dilution can be helpful as it can aid in accurately measuring absolute volumes of TBW and differential fluid compartments. The time, expertise, and equipment sophistication required for monitoring dehydration through isotope dilution limits the use of the methodology [20]

- Symptom-based scales: Multifactorial assessment scales have been developed to improve the diagnostic performance for dehydration to combine multiple signs and symptoms as individual signs and symptoms have been shown to be of low sensitivity for dehydration[21] It has been observed that the performance of symptomatology-related scales would likely be worse in the absence of highly trained clinical personnel.[22]

- Blood, Urine, and Body Mass Loss: These are the most commonly deployed measurements for dehydration. To test the diagnostic accuracy of these methods, very few studies have been conducted and to summarise the results of two carefully controlled studies: For dynamic dehydration assessment, only plasma osmolality (Posm), urine specific gravity, and BML had validity; and for static (single-point) assessment, only Posm greater than 301 mmol/kg had validity (demonstrated prospectively) to diagnose dehydration). There has been unsurity about the generalization of these methods to each individual across different populations and if they are reliable enough for diagnosis. [23] Another study concluded the lack of diagnostic utility of both physical signs and urine markers

[19] Cheuvront et al., "Biological Variation and Diagnostic Accuracy of Dehydration Assessment Markers."
[20] Gray, Birkenfeld, and Butterworth, "Noninvasive Monitoring to Detect Dehydration."
[21] Hooper et al., "Clinical Symptoms, Signs and Tests for Identification of Impending and Current Water-Loss Dehydration in Older People."
[22] Gray, Birkenfeld, and Butterworth, "Noninvasive Monitoring to Detect Dehydration."
[23] Gray, Birkenfeld, and Butterworth.

reinforcing the need for a convenient and non-invasive method to monitor dehydration. [24]

Current methods for hydration monitoring

There have been various kinds of approaches made to detect changes in hydration status. Some approaches have been through the measurements of body fluids like saliva or sweat and some have been by interrogating the tissue's response to electromagnetic input signals with the help of electromagnetic tissue probes. As per a review, even though all these methods based on physical principles are sensitive to water with some potential to provide some measure of dehydration, only a few have been clinically used without any demonstration of their performance outside the context of the study population. There have been reviews to gauge the diagnostic accuracy of technologies like Bioimpedance spectroscopy, Gigahertz dielectric spectroscopy, Infrared Spectroscopy, Raman spectroscopy, Capillary Refill Time, Nuclear Magnetic Resonance, Ultrasound Velocity, Sweat Composition Analysis, Saliva Osmolality. It should be noted that none of these have been rigorously evaluated for their diagnostic accuracy and developed to a point where they have been proven to be appropriate for use in a non-clinical setting to either diagnose or screen for dehydration.

Gigahertz- and Terahertz-Range Dielectric Spectroscopy: At gigahertz and terahertz frequencies, impedance is biased towards a measure of the amount of energy from an external electrical field stored in the material it is measuring. At all kinds of frequencies, these measurements are dependent on the volume of water that 'sees' the electric field. The sensing volume is localized near the electrode and depends on the frequency along with the geometry of the electrode at high gigahertz and terahertz frequencies. [25] [26] A coaxial probe and a vector network analyzer (VNA) is used generally to capture experimental measurements of dielectric properties of biological materials, it has been observed that the geometry or the probe as well as that of the material under test, is what the relationship

[24] Hooper et al., "Clinical Symptoms, Signs and Tests for Identification of Impending and Current Water-Loss Dehydration in Older People."
[25] Porter and O'Halloran, "Investigation of Histology Region in Dielectric Measurements of Heterogeneous Tissues."
[26] La Gioia et al., "Open-Ended Coaxial Probe Technique for Dielectric Measurement of Biological Tissues."

between the measurement and electrical properties depend on. [27] [28] The dimensions and specs of a probe are an important factor in some of the following ways:

- The volume of material probed is in the region near the probe and depends on the probe's dimensions: The volume that is 'seen' with a probe is restricted in the region near the probe and is strongly dependent on the size of the probe and the effective permittivity.

- Correlation of the depth of the sensing volume with the frequency: For a particular probe, there is a decrease in the depth of the sensing volume with increasing frequency, this depth in typical setups is in the order of millimeters for gigahertz measurements to microns for terahertz measurements [29] [30][31]

Multiple studies have shown these approaches being used in imaging nodes to identify regions of differing water content for potential applications in skin and breast cancer, and skin burns. For this thesis, the technology used to sense dehydration is the Gigahertz range as there has been evidence to support the dependence of dielectric properties on tissue hydration in living tissues. As per a review of emerging technologies [32] , its use to measure hydration status in humans is unknown so far.

Static measurements vs Dynamic measurements

For clinically meaningful measurement, most technologies have a likelihood of detecting a change in hydration instead of providing a single-point measure of hydration status; this makes a means of establishing a baseline necessary but can be overlooked. Static or single-point measurements provide an individual's hydration status without any baseline reference. This is not feasible for most of the measurement approaches as there can be large interindividual differences in the hydration levels. Dynamic or multipoint measurements map a change generally in reference to a euhydrated (the state of optimal TBW) baseline. The real-world use of this strategy will depend on methods for knowing the baseline.

---

[27] "Basics of Measuring the Dielectric Properties of Materials."
[28] "Microwave Dielectric Spectroscopy Workshop 'Measure the Difference.'"
[29] La Gioia et al., "Open-Ended Coaxial Probe Technique for Dielectric Measurement of Biological Tissues."
[30] Porter and O'Halloran, "Investigation of Histology Region in Dielectric Measurements of Heterogeneous Tissues."
[31] Meaney et al., "Microwave Open-Ended Coaxial Dielectric Probe."
[32] Gray, Birkenfeld, and Butterworth, "Noninvasive Monitoring to Detect Dehydration."

Current products in the market for hydration monitoring

- Sweat Patches: The Gatorade sweat patch is a commercial product marketed by Gatorade for use in sports and performance monitoring. The combination of a microfluidic patch and advanced image processing software allows for the instant evaluation of sweating rate and sweat chloride concentration in individuals engaging in typical exercise routines at home or remote locations. By utilizing this affordable wearable sensing system, it becomes possible to gather data on sweat electrolyte loss and sweating rate, enhancing the availability of sweat analytics in practical scenarios. This technology offers numerous applications, not only in optimizing athletic performance but also in offering valuable guidance for hydration strategies to avoid severe dehydration or excessive fluid intake among fitness enthusiasts and casual exercisers.[33] Some studies have evaluated the use of sweat patches for monitoring hydration status and electrolyte loss during exercise, but these studies have typically used research-grade patches, rather than the Gatorade brand patch specifically. While sweat patches can provide valuable information about hydration status and electrolyte loss during physical activity, they are not yet widely used in clinical or research settings due to limitations such as cost, variability in sweat composition between individuals, and the need for more validation studies.

- Patents that have not made it to the market yet: One such patent, titled "Hydration measurement with a watch," was granted to Apple in 2018. It describes a system that uses electrodes for measuring the electrical properties of perspiration. The patent describes a wearable electronic device, such as an Apple Watch, that provides helpful feedback related to hydration levels based on their perspiration rate. There have been multiple such patents filed by numerous companies but the technology for most of these has not been made available in the market yet. [34]

- Kickstarter LVL case study: The LVL hydration monitor was supposed to be a wearable device that tracks hydration levels by measuring biomarkers in the wearer's sweat. Designed to be worn on the wrist like a fitness tracker, the device was supposed to use red and infrared light to measure blood flow, heart rate, and other metrics, in addition to hydration. The device proposed real-time feedback on hydration levels, as well as personalized hydration recommendations based on the wearer's activity level and other factors. Developed by BSX Athletics, an Austin-based wearable sensor company had raised $1.2 million on Kickstarter to develop the product back in 2016 and has recently

[33] Baker et al., "Skin-Interfaced Microfluidic System with Machine Learning-Enabled Image Processing of Sweat Biomarkers in Remote Settings."
[34] "One of the next Health Features That May Be Coming to Apple Watch Relates to Tracking Hydration Levels of a User."

refunded the backers following years of silence regarding the development of the technology.[35]

Need for non-invasive dehydration monitoring in a non-clinical setting

There is a significant need for hydration monitoring particularly for the elderly and very young populations who tend to be more vulnerable. There is a lack of suitable noninvasive assessment methods to detect mild to moderate dehydration so that action can be taken before requiring medical attention. The commercial interest in this space has been exciting with multiple approaches which theoretically are sensitive to changes in water. With this thesis, we are trying to get a little closer to testing the hydration sensor developed based on Gigahertz Dielectric Spectroscopy.

Wearables

Wearables refers to technology that can be worn, creating a close and personal connection with the user. Wearable devices have found diverse applications in healthcare, encompassing a wide range of physiological and neurocognitive conditions. These applications extend from cardiovascular diseases, hypertension, and muscle disorders to neurocognitive disorders like Parkinson's disease, Alzheimer's disease, and various psychological conditions. To cater to these medical needs, different types of wearables are utilized, including skin-based wearables such as tattoo-based wearables, textile-based wearables, and biofluidic-based wearables. [36]

Wearable technology encompasses more than just the physical devices worn on the wrist, neck, or clothes; it also includes the intangible services, culture, and behaviors associated with these devices, which give them their true power. Wearables are not solely about placing computers on our bodies; they have the potential to transform the way we live and interact with our bodies and each other. In wearables, two crucial aspects relate to human interaction: input, which focuses on how we provide information to the computer, and output, which concerns how the computer presents information to us. These aspects play a significant role in shaping the wearable experience (Sullivan, 2016, Foreword).

Input

There are two primary types of input for wearable devices: detailed input and passive input. Detailed input involves tasks like text input and object manipulation, typically done on desktop computers. Efficient methods include using phones as temporary keyboards or voice

---

[35] "LVL – The First Wearable Hydration Monitor."

[36] Sullivan, *Designing for Wearables : Effective UX for Current and Future Devices*.

commands. Passive input collects data without active user engagement, such as steps, heart rate, and GPS location. Fitness trackers are a common example. Humanyze, a spinoff from MIT Media Lab, uses sensor-equipped lanyards to track employee location and analyze social interactions within a company's building.

Output

Output presents a relatively simpler challenge when it comes to wearable devices. It can be categorized into active and passive forms. Active outputs require attention and include notifications, displays, and interactions. Passive outputs provide continuous information without demanding full attention, like vibrating reminders or glanceable interfaces. Examples include the Lumo Lift, a posture coach that vibrates, and Withings Activité watches with a passive interface.[37]

Non-Invasive Wearables

Non-invasive wearables are devices that can be worn on or attached to the body without the need for invasive procedures or direct contact with bodily tissues or fluids. These wearables are designed to collect data and provide insights about various aspects of an individual's health, fitness, or daily activities. They offer a convenient and user-friendly approach to monitoring and tracking without requiring surgical implantation or invasive methods.

Skin, being the largest organ of the human body, presents an ideal platform for noninvasive healthcare wearable devices. Utilizing skin-based wearables allows for the monitoring of physiological and psychological parameters crucial in the treatment of various diseases, including cardiovascular and neuromuscular conditions. These devices offer the potential for disease diagnosis through the analysis of skin secretions, such as sweat, using qualitative and quantitative methods.

There are different types of non-invasive wearable sensors used for diagnosing various physical, electrophysiological, and biochemical properties of the human body.

- **Physical Sensors**: These sensors record physical parameters such as movement-induced strain and temperature. They can be incorporated into clothing or placed directly on the skin to detect strain derived from bodily motion. Examples include carbon nanotube sensors and an ionic liquid-based sensor patch.
- **Electrophysiological Sensors**: These sensors collect electrical signals from the body, such as ECG, EEG, and EMG. They are designed to access physiological data non-invasively and are composed of soft, stretchable substrates with biocompatible electrodes. Examples include epidermal sensors for ECG and EEG recording.

[37] Sullivan.

Biochemical Sensors: These sensors analyze ions, biomolecules, electrolytes, and proteins present in bodily fluids, with a focus on sweat for non-invasive biochemical analysis. They use soft, stretchable microfluidic systems with specialized receptors (enzymes or antibodies) that interact with target ions. Examples include wearable microfluidic devices for sweat analysis and a skin-like sensor for glucose monitoring. [38]

Common non-invasive wearables

1. Fitness Trackers: These devices are commonly worn on the wrist and monitor metrics like steps taken, distance traveled, heart rate, sleep patterns, and calorie expenditure.
2. Smartwatches: Smartwatches offer a range of features beyond fitness tracking, including notifications, GPS navigation, music control, and customizable apps. They often include sensors to monitor heart rate, activity levels, and sleep patterns.
3. Smart Clothing: This category includes garments embedded with sensors or conductive fabric that can track biometric data such as heart rate, respiration rate, and body temperature. Smart clothing is often used in sports and fitness applications.
4. Sleep Trackers: These devices are designed to monitor and analyze sleep patterns, including duration, sleep stages, and quality. They can be worn as wristbands or placed near the bed.
5. Posture Correctors: These wearables are typically worn as straps or braces and provide feedback or vibrations to improve posture and reduce slouching.
6. Blood Pressure Monitors: Non-invasive blood pressure monitors use cuff-based or wrist-based sensors to measure blood pressure without the need for invasive procedures.
7. Breath Analyzers: These devices analyze breath samples to provide insights into various health parameters, such as hydration levels, metabolism, or indicators of certain medical conditions.
8. Activity Trackers: Activity trackers monitor physical activities such as steps, distance, calories burned, and active minutes. They are often compact and worn on the wrist or clipped onto clothing.
9. Pulse Oximeters: These devices measure oxygen saturation levels in the blood by clipping onto a finger or earlobe. They are commonly used for monitoring respiratory health and during exercise.

[38] "Wearable Devices for Non-Invasive Sensing."

10. Smart Glasses: Smart glasses incorporate heads-up displays, enabling users to view information or receive notifications directly in their field of vision. They can be utilized in various industries, including healthcare and augmented reality applications.

These are just a few examples of non-invasive wearables, highlighting the wide range of devices available for monitoring and improving various aspects of health, fitness, and daily life.

Fitness trackers & wearables

According to a study conducted by Valencell and the MEMS & Sensors Industry Group, there is a growing demand among individuals for biometric wearables that can monitor their health and fitness. The study revealed that 55% of respondents expressed a desire to monitor their stress levels, recognizing the importance of managing this aspect of their well-being. Additionally, **48% of participants expressed an interest in monitoring their hydration levels**, understanding the significance of maintaining proper fluid intake. The study also highlighted that 46% sought blood pressure monitoring, 38% were interested in sunlight/UV exposure monitoring, and 35% wished to monitor key vitamin and supplement levels. Over half of the respondents who do not currently own a wearable expressed their willingness to purchase one if they trusted its accuracy.[39]

A study conducted by Gartner surveyed 706 consumers in the United States. Among the respondents, 43% already owned a wearable device, with 63% considering accuracy as a highly important feature. Following accuracy, comfort (57%) and battery life (47%) were ranked as significant factors. The study also revealed that the abandonment rate for smartwatches stands at 29%, while it is 30% for fitness trackers. Reasons for abandonment included a lack of usefulness, boredom, and device malfunction. Many users discontinued the use of wearable tech within a few months. Common reasons cited for discontinuation included the inconvenience of recharging, lack of trust in data accuracy, and dissatisfaction with the devices overall.

The survey highlighted that the designs of smartwatches and fitness trackers were not appealing to consumers. To address this concern, Gartner suggested that wearable providers collaborate with companies experienced in designing, branding, marketing, and distributing fashion accessories and watches. These partners can offer expertise in setting style trends, marketing lifestyle devices, and utilizing established retail channels.

Furthermore, the survey found that 29% of respondents considered fitness trackers unattractive, stating that they would not wear them due to their unfashionable and

[39] Valencell, "National Wearables Survey Reveals Accuracy Is Top Priority Among Consumers; Lack of Continually Interesting Insights Among Top Reasons for Discontinued Use."

unappealing designs. Mikako Kitagawa, principal research analyst at Gartner, noted that fashion brands often sell fitness tracker cases and wristbands as higher-priced upgrades, which could act as a barrier to purchase.[40]

Interestingly, individuals below the age of 45 tended to believe that a smartphone could fulfill all their needs, resulting in reduced interest in fitness trackers. Meanwhile, respondents aged 45 and above expressed that they had no plans to purchase fitness trackers due to their perceived high cost in relation to the value they provide.

In an effort to integrate wearables seamlessly into daily life, there are ongoing efforts to make them smaller, more flexible, stretchable, and even washable. Some envision future wearables to be "invisible," blending into clothing or adapting to the body. Veena Misra, Ph.D., director of the ASSIST Center, funded by the National Science Foundation, shared the concept of shirts with invisible sensors woven into the fabric or devices so minuscule that they can be concealed under a fingernail or even implanted inside the body.[41]

IoT and wearables in health monitoring

The Internet of Things (IoT) and wearable devices have transformed various aspects of society, including healthcare and disease management. These technologies enable remote monitoring, real-time data collection, and predictive analysis, revolutionizing the way healthcare is delivered. The following examples highlight several ongoing developments in IoT wearable devices and their applications in healthcare:

1. Continuous glucose monitoring systems: Wearable devices like Dexcom and Eversense monitor glucose levels for people with diabetes, enabling better insulin delivery and management.
2. Wearable devices for heart attacks: Wearable defibrillators and implantable defibrillators help treat life-threatening heart rhythms and prevent sudden death in patients with tachycardia or arrhythmia.
3. Protection against concussion: The Q-Collar is a wearable device that stabilizes the brain inside the skull, reducing the risk of concussions caused by sports traumas or repeated hits.
4. Sensors for stroke patients: Electromyography (EMG) sensors assist in muscle rehabilitation and monitoring for prosthetic patients and those recovering from a stroke.

[40] "Gartner Survey Shows Wearable Devices Need to Be More Useful."

[41] "Our Wearable Future, Part 1: What Will New Tech Look Like?"

5. Asthma monitoring wearable technology: Intelligent Asthma Monitoring devices can predict and prevent asthma attacks by detecting symptoms like coughing or shortness of breath.
6. Movement disorders: Apple Watch can measure and record dyskinetic symptoms and tremors in patients with movement disorders like Parkinson's disease.
7. Coagulation monitoring: Bluetooth-enabled coagulation systems allow patients to monitor their blood clotting levels in real-time, reducing the need for frequent clinic visits.
8. Smart contact lenses: CE-marked and FDA-approved smart contact lenses can automatically record changes in eye dimensions and detect ocular deterioration, aiding in early glaucoma detection.
9. Monitoring medical adherence: Wearable smart necklaces use Bayesian networks to assess medication adherence based on swallowing movements, helping patients with hypertension, diabetes, and other conditions.
10. Cancer treatment: Bluetooth-enabled weight scales and blood pressure cuffs linked to symptom-tracking apps improve symptom management and treatment response for cancer patients.
11. Posture correction: Upright Go is a wearable device that provides biofeedback to train users to maintain a healthier posture and reduce spinal problems.
12. Hearing aid: Digital hearing aids analyze speech and environmental sounds, providing precise sound duplication and enhancing hearing for people with hearing disabilities.
13. Sleep monitoring: Wearable devices like Beddit measure sleep time, heart rate, and other factors, offering recommendations for improving sleep patterns.
14. Early detection of Alzheimer's: Efforts are underway to develop cost-effective and non-invasive wearables that can detect Alzheimer's disease at its earliest stages, facilitating early intervention.
15. Hospital internal monitoring: IoT devices track the location of medical equipment and staff in real-time, improving efficiency and ensuring hygiene standards.
16. Respiratory disease detection: Wearable respiratory monitoring sensors detect changes in breathing patterns, heart rate, and temperature, alerting patients and medical professionals to potential lung function deterioration.
17. Artificial kidneys: Advances in wearable technology may lead to the development of artificial kidneys, offering an alternative to in-hospital hemodialysis for patients with kidney failure.
18. Blood sensors: Wearable sensors utilizing infrared laser absorption spectroscopy remotely test the concentration of blood elements such as glucose, ketones, and urea, benefiting individuals with chronic health conditions like diabetes.

19. Lung monitoring: The WELMO project aims to develop miniaturized sensors integrated into intelligent vests to monitor lung function and treat chronic obstructive pulmonary disease more efficiently.[42]

These ongoing developments demonstrate the potential of IoT and wearable devices to revolutionize healthcare by enabling remote monitoring, early detection, and personalized treatment approaches.

Designing wearables for older adults

In a study conducted with diabetic patients aged sixty years and above, it was discovered that the perceived usefulness of digital health wearables has a significant impact on the intention of elderly diabetic patients to use them. This indicates that if wearables meet the expectations of elderly diabetic patients in terms of increased productivity and convenience, it influences their intention to continue using the technology. The research findings indicated that the elderly diabetic patients' intention to persist in utilizing digital health wearables is positively influenced by their perception of the devices' ease of use. Essentially, if the learning process to operate these devices is easy for the elderly patients, it becomes a major factor in their decision to keep using the technology.

Additionally, the study found that four other factors, namely perceived irreplaceability, perceived credibility, compatibility, and social influence, have a positive impact on the intention of elderly diabetic patients to continue using digital health wearables. The first factor, perceived irreplaceability, suggests that these wearables fulfill the specific health-related needs of elderly diabetic patients in a way that traditional devices like passometers cannot, leading them to continue their usage. The second factor, perceived credibility, indicates that elderly diabetic patients trust that digital health wearables protect their personal health information, which encourages them to continue using them. The third factor, compatibility, suggests that these wearables seamlessly integrate with the existing devices of elderly diabetic patients, such as smartphones, making them more likely to continue using them without hesitation. The fourth factor, social influence, highlights the impact of friends, family members, and colleagues on the intention of elderly diabetic patients to continue using digital health wearables. Given that elderly diabetic patients value their opinions, they tend to continue using the technology based on their recommendations.[43]

---

[42] "20 Examples Of IoT Wearables Technology Disrupting Healthcare – Avenga."

[43] Ahmad et al., "Understanding Factors Influencing Elderly Diabetic Patients' Continuance Intention to Use Digital Health Wearables."

Design Principles for Wearables:

The primary obstacle facing wearable technology trends in the industry is to ensure lasting customer engagement. Issues such as low-quality products, difficulty in syncing with smartphones, short battery life, uncomfortable and unattractive designs, and poor user interface and experience contribute to user dissatisfaction and device abandonment. This, in turn, negatively affects the wearable app industry as a whole. While wearable technology is seen as a disruptive force in the business world, it also brings concerns regarding data security and privacy risks. [44]

The following are some key design considerations while designing wearable devices in a rapidly expanding technological landscape.

1. Understanding User Needs: When it comes to design, the initial priority is to comprehend the user and their particular requirements. This understanding guides the determination of what aspects need to be measured. It also influences the choice of sensor and establishes the overall system structure, encompassing data collection, processing circuitry, and power consumption.
2. Choosing the Best Sensor Location: Different body locations present unique considerations for sensor placement, with certain parameters only obtainable from specific locations.
3. Considering Form and Function: The aesthetics and appeal of wearable devices are important for user acceptance and adoption. The form should be as attractive as the technology itself.
4. Displaying Data: User interface design plays a crucial role in presenting captured data. The display should be tailored to the target audience and their specific interactions and preferences.
5. Connectivity: Seamless connectivity is essential for a smooth user experience. The choice of communication technology depends on the application, ranging from Bluetooth for short-range connections to cellular connectivity for roaming devices.
6. Translating Data Into Action: Effective analysis of collected data is vital for transforming raw data into valuable information and actionable insights. Decisions need to be made regarding data processing location and the intended end user.

Currently, a significant portion of the data collected from different wearable devices is fragmented and lacks compatibility, offering limited practical value. The true obstacle in fully

[44] "Designing For Wearable Devices."

leveraging wearables as part of the Internet of Things is to establish connections between these isolated data sources and integrate them in a manner that allows for meaningful correlations. This integration has the potential to provide fresh perspectives and insights into both individuals and the surrounding environment. [45]

[45] "6 Considerations for Designing a Wearable Device."

Chapter 2: Hydration@mit

About Splash

The Hydration team at MIT has been working on a technology that could revolutionize hydration management, with the potential to significantly improve quality of life, survival rates, and make hydration monitoring possible. The Hydration project at MIT aims to develop a simple and non-invasive hydration monitor for clinical and non-clinical use, that simplifies hydration monitoring and enables improved hydration management for self-care and the care of others.

Measurement method

The GHz-range measurement modality (dielectric spectroscopy) has been widely used in industrial applications, but is now possible in consumer-appropriate small and power-efficient form factors, through the advent of miniaturized & performance-optimized electronic chipsets that are now available. A noninvasive radiofrequency-based sensor, using the GHz range, a frequency regime that is specific to water, allowing noninvasive assessment of tissue water content, is designed at MIT to measure tissue water content in a local superficial tissue volume. It fits into the “minimal risk” FDA classification and conducts ultra-low power electrical measurements of the tissue to measure water content, based on electromagnetic fields that are highly similar to that of “low energy Bluetooth” (a very common communications technique incorporated in existing wearable devices, i.e. fitbit, apple watch).
The group has validated the GHz-range measurement that is at the core of the technology against laboratory tissue models, demonstrating repeatable sensitivity to water content in tissue. A previous lab study conducted to establish an easy to use and tunable tissue phantom to use in evaluating RDS technologies for their potential to measure hydration of biological tissues concluded that IPA-water phantoms provide a suitable tissue phantom for exploring the feasibility of monitoring water volume fraction using reflectance-mode dielectric spectroscopy (RDS) S11 measurements in the 2-6 GHz range. In the range of 60-90% water, as shown in Figure 1, a range that covers that typical dermal tissues, the GHz-range approach demonstrates excellent sensitivity and linearity, with repeatability error below the target minimal detectable change of 1-2% water.

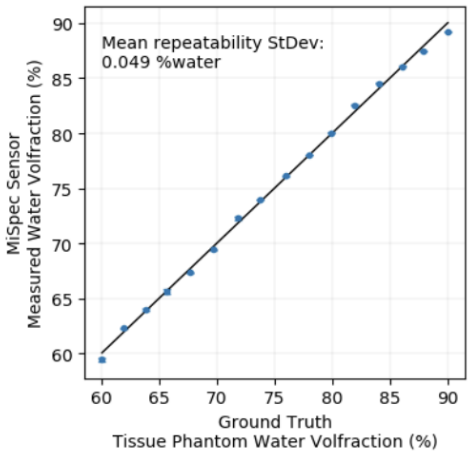


Figure 1: Sensitivity to Water Percentage in Tissue Phantoms

In previous laboratory studies, the GHz-range measurement approach has been proven effective in detecting mild dehydration and subsequent rehydration. However, these studies utilized a tabletop device where measurements were obtained by placing a finger into a guided channel in the portable device. During the measurement process, the sensor was lightly pressed onto the pad of the fingertip for up to 10 seconds before being released.

The study protocol involved several key steps. Firstly, a baseline measurement session was conducted on day 1, during which device measurements were taken, and a blood draw was performed. Subsequently, participants were instructed to fast overnight and return the next day to engage in exercise while maintaining the fasted state, thereby inducing dehydration. This phase consisted of a series of exercise, rest, and measurement cycles repeated over a 4-hour period. Following the exercise session, participants were allowed to eat and drink freely. To evaluate the effects of dehydration and monitor changes in hydration status, a follow-up set of measurements was conducted on the subsequent day. This comprehensive study design aimed to capture data during different phases, including the baseline, fasting, exercise-induced dehydration, and post-rehydration periods.

While these previous laboratory studies provided valuable insights into the efficacy of the GHz-range measurement approach, they were limited to a tabletop device and required specific protocols for measurement acquisition. To further advance the field and enable real-world applications, it is imperative to develop a wearable setup that allows for continuous and non-invasive monitoring of hydration levels.

By transitioning from a tabletop device to a wearable configuration, the research can capture hydration data with the probe being on the body for a long time. The wearable setup offers the potential for more convenient and continuous monitoring, enabling the collection of data during daily routines, physical exercise, and other real-life contexts. This transition from

controlled laboratory studies to wearable technology represents a crucial step towards the practical application of hydration monitoring by further validating the technology.

To fully validate and establish the utility of this technology, it is crucial to conduct extensive testing outside of the controlled laboratory environment. The primary objective of this thesis is to address this need by developing a wearable setup that enables longer-duration human studies. The aim is to create a robust data package that supports the hypothesis that the proposed measurement approach can effectively detect changes in hydration levels. By designing a wearable device, the research can extend beyond the confines of the laboratory and capture hydration data in diverse real-life contexts, including daily activities, physical exercise, and various environmental conditions. The wearable setup serves as a means to bridge the gap between controlled laboratory studies and real-world applications. By enabling participants to wear the device comfortably and conveniently throughout extended periods, the research can capture a more comprehensive range of hydration data, including variations in hydration levels during different activities, sleep, and fluctuations over time.

Chapter 3: Thesis Objective and Hypothesis

Thesis Objective

The objective of this thesis is to provide further validation for the functionality of the hydration sensor developed by the research group. To accomplish this, the goals of the study are divided into the following steps:

1. Development of a setup and implementation of a protocol that enables individuals to effectively "wear" the proposed hydration sensor for a minimum duration of 24 hours. This step aims to establish a practical and comfortable method for users to incorporate the sensor into their daily routines while participating in the human study.
2. Evaluation of how the sensor readings vary over time throughout the day and night, while the wearer engages in their regular activities. This investigation seeks to understand the dynamic nature of hydration levels and how they fluctuate in response to different activities and environmental conditions.
3. Determination of whether the sensor readings can effectively differentiate between prolonged periods of dehydration and normal hydration levels during routine activities. This analysis aims to validate the sensor's ability to accurately detect and identify states of dehydration in comparison to adequately hydrated states.
4. Conceptualization of future iterations of the wearable hydration sensor and development of design concepts. This step involves utilizing the insights gained from the study to inform the refinement and enhancement of the wearable device for hydration monitoring purposes.

Based on these outlined goals, the research was structured around two main research questions. These questions were formulated to provide a framework for organizing and conducting the necessary research activities related to the validation and improvement of the hydration sensor technology.

Research Question 1

What is the optimal wearable setup and usage protocol for conducting human studies and collecting continuous data for a minimum duration of 24 hours to monitor hydration levels?

Research Question 2

What is the extent of natural variation observed in a euhydration study, and how does this variation change when individuals experience dehydration? Can physiological changes associated with dehydration be detected in the data collected during human studies?

Hypotheses

The central hypothesis of this thesis is that a wearable setup can be developed which would have the potential to detect and measure changes in hydration levels outside of a controlled laboratory environment. The objective is to assess the sensitivity of the technology and its ability to accurately capture hydration-related variations in real-world settings.

Chapter 4: Research Methods

The research methods employed in this study were divided into three main parts: the development of the wearable setup, the establishment and approval of the human study protocol, and the execution of the human studies. The development process for the wearable setup commenced in January 2022, obtaining COUHES approval in November 2022, with the official commencement of the human studies taking place in December 2022. These stages underwent multiple iterations based on experimental findings and insights gained throughout the development phases.

Chapter 5 of the thesis details the design process undertaken to adapt the existing device into a wearable format suitable for use by participants outside of the laboratory setting. This involved defining design constraints, establishing design criteria, generating ideation, creating sketches, iterating through prototype development, and finalizing the design. Emphasis was placed on attributes such as comfort, stability, durability, continuous body contact, and optimal data collection. Various prototyping tools, including 3D printing, paper prototyping, and cloth prototyping, were utilized to refine and perfect the wearable setup.

Chapter 6 focuses on the protocol employed to conduct the human studies using the wearable setup, with the aim of monitoring subtle fluctuations in hydration levels within the human body. The protocol encompasses various components of the study, such as participant recruitment, the consent process, the testing procedure, and post-completion surveys. Approval for the protocol was obtained from the Committee on the Use of Humans as Experimental Subjects (COUHES) at MIT, with iterative revisions to ensure participant safety and privacy throughout and following the research. The participants were divided into two cohorts: the Euhydration cohort and the Dehydration cohort, comprising a total of 16 individuals.

Chapter 7 outlines the methods employed to analyze the data collected during the human studies. Different approaches were utilized to comprehend and visualize the data obtained from both the Euhydration study and the Dehydration study. Tools such as Python, Excel, and Figma were employed to plot, analyze, and visualize the data, enabling the identification of any physiological changes represented in the data and facilitating a comparison between the Dehydration and Euhydration cohort data.

Throughout the research and design process, a variety of design tools were utilized to facilitate the development and refinement of the wearable setup. These tools included RedCap, Miro, Rhino 3D, Keyshot, Fusion 360, Figma, and various others. These design tools

played a crucial role in different aspects of the research, enabling tasks such as data collection, collaborative brainstorming, 3D modeling, realistic rendering, and interactive design prototyping. By leveraging these tools, it was possible to enhance the efficiency and effectiveness of the design process, ultimately contributing to the successful development of the wearable setup.

Chapter 5: The Wearable setup

The primary goal of this project phase was to prepare the existing device for testing in outside the laboratory environment. Despite its bulkiness, it was imperative to configure all the components in a way that would allow the device to be comfortably worn by human study participants throughout their daily activities.
The focus was on optimizing the device's design and functionality to ensure ease of use and wearability. Various adjustments and refinements were made to work with the device's size and weight, while maintaining its essential features and capabilities.
By configuring the components, the device became more practical and user-friendly, enabling seamless integration into participants' daily routines. This transformation was vital in facilitating long-term and non-intrusive data collection, as participants could wear the device comfortably and engage in their regular activities without disruption.
The aim of this phase was to achieve a balance between functionality and wearability, ensuring that the device was not only capable of collecting accurate data but also convenient and unobtrusive for study participants.

Current Device Setup

The current device setup encompasses both hardware and software components to enable the acquisition and analysis of pertinent data. The hardware aspect involves a probe that establishes direct contact with the skin, allowing for accurate measurements. This probe is connected via wires to a measurement system powered by a battery pack/ power bank. The measurement system consists of a Nano-VNA, a Raspberry Pi, and temperature sensors, which work in tandem to capture relevant RF (radio frequency) and temperature readings.
To facilitate data storage and subsequent analysis, the measurement system records the acquired RF and temperature measurements on an SD card. This approach ensures that the data is securely stored and readily accessible for processing once the study is completed.
The software setup, depicted in Figure 2, plays a vital role in coordinating and managing the data collection process.
The outcomes generated by this device setup manifest in the form of tissue water percentage through S11 magnitude and change in hydration percentage, which are key metrics for assessing hydration levels. The tissue water percentage readings have undergone calibration through the utilization of tissue phantoms within a laboratory setting. This calibration process ensures the accuracy and reliability of the tissue water percentage measurements, thereby enhancing the validity of the collected data.

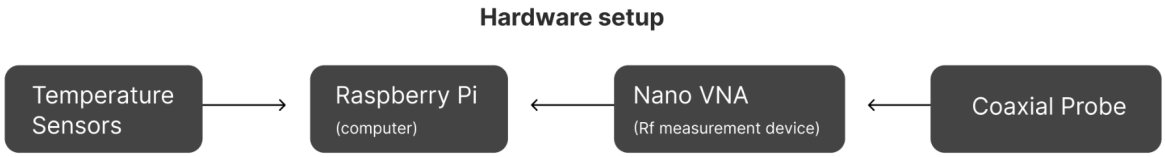


Figure 2: Hardware setup of the current device

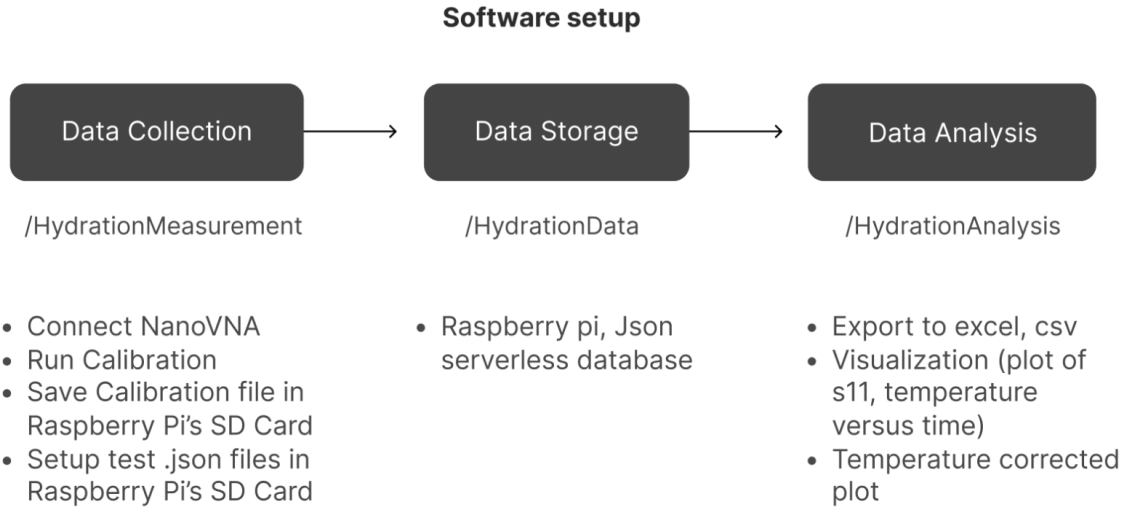


Figure 3: Software setup of the current device and methodology to setup experiments

The process shown in Fig. 3 for the software setup is also the process that is followed for each experiment conducted through the device to collect data. The data collection and analysis process for the experiment is outlined below, and all the collected data is stored in the "/HydrationMeasurement" and the "/HydrationAnalysis" directory:

1. Measurement:
    a. Connect the NanoVNA device to the laptop using the appropriate cables.
    b. Perform the calibration procedure to ensure accurate measurements. This involves following specific steps using the NanoVNA's calibration features.
    c. After completing the calibration, save the calibration file on the Raspberry Pi's SD card under the calibration folder of the study's parent folder. This file contains the calibration settings and parameters.
    d. Set up the necessary test files for the experiment. These files, typically in the JSON format, contain the required configurations and parameters for data collection.
    e. Update the experiment name in the run script file located on the SD card. This ensures that the data collected during the experiment is properly associated with the corresponding experiment.

2. Data analysis process for the experiment conducted can be outlined in the following steps:
    a. In the Hydration analysis directory, create a configuration file specific to the experiment conducted. This file contains relevant settings and parameters necessary for the analysis.
    b. Import the folder containing the data from the SD card into the Hydration Analysis folder. This folder should be placed within the corresponding experiment's folder to ensure proper organization and association of the data.
    c. Run the analysis code with the "-excel" tag to generate an Excel file containing the s11 magnitude, time, and temperature data.
    d. Visualize the data by creating plots of the s11 magnitude and temperature against time. These plots provide a graphical representation of the data, allowing for visual inspection of trends, patterns, and correlations and will be covered in the Chapter 7.
    e. Apply temperature correction to the plotted data. This correction step involves adjusting the dependency of s11 magnitude data points on the recorded temperature values during the experiment. By accounting for temperature variations, the corrected plot ensures more accurate and reliable analysis results.

Calibration

NanoVNA's Calibration is a crucial step performed before each experiment and whenever there is a change in the frequency range to be measured. It ensures accurate measurements by accounting for system-specific characteristics and minimizing errors. The calibration load utilized in this process comprises an open, a short, and a 50-ohm unit, which serve as reference points for calibration. The following method outlines the steps for running the calibration process:

1. Create a new .json file: In the designated directory structure, specifically within the "Hydration measurement > data > [test folder]" hierarchy, generate a new .json file. This file will be used to store the calibration data obtained during the process.
2. Connect the NanoVNA to the laptop: Establish a physical connection between the NanoVNA and the laptop using the appropriate cable. This connection facilitates communication and data transfer between the devices.
3. Run the calibration script: Within the coding environment, such as Visual Studio Code, execute the calibration script by running the command "python3 vnacal.py -cf ./data/path.json". This command triggers the calibration procedure and initiates the

necessary computations.

```
salonibedi@C02FK930MD6M HydrationMeasurement % python3 vnacal.py -cf ./data/weartest/weartest_2.j
son
```

4. Follow the prompts: The script will provide prompts and instructions within the coding environment. Adhere to these prompts, which guide the placement of the Short, Open, and Load units on the cable opening during the calibration process. While tightening the Short, Open, and Load units, a torque wrench compatible for RF connectors is used.
5. Save the calibration file: Once the calibration process is completed, save the calibration file in the corresponding study folder. This file contains the calibrated data and will be utilized during the ongoing study.

By following this method, the calibration process is effectively executed, providing calibrated data for subsequent measurements in the study. The saved calibration file serves as a reference for accurate measurement calculations, enabling reliable and precise data analysis throughout the research.

On-Device Calibration

In addition to the calibration procedure described earlier, an alternative method is available for conducting on-device calibration using the NanoVNA's screen. This method allows the observation of real-time readings through the probe, offering a look into the condition of the cable and any potential fluctuations caused by its movement. This calibration cannot is not an alternative to the previous one though as it cannot be stored in the raspberry pi. The following steps outline the process for conducting on-device calibration:

1. Attach a power source to the NanoVNA: Ensure the NanoVNA is connected to a suitable power source, providing the necessary energy for operation.
2. Connect the coaxial cable to the NanoVNA: Establish a secure connection between the NanoVNA and the coaxial cable. This connection facilitates the transmission of signals and measurements.
3. Follow the calibration menu map: On the NanoVNA's screen, navigate to the calibration menu, as illustrated in Figure 4. Within this menu, select the Open, Closed, and Load options one by one, ensuring that the corresponding calibration units are properly connected before the option is selected and a reading is taken.
4. Access real-time readings: Return to the main screen of the NanoVNA, where real-time readings can be accessed. These readings, displayed at the top of the screen, provide immediate feedback on the measurements obtained through the probe.

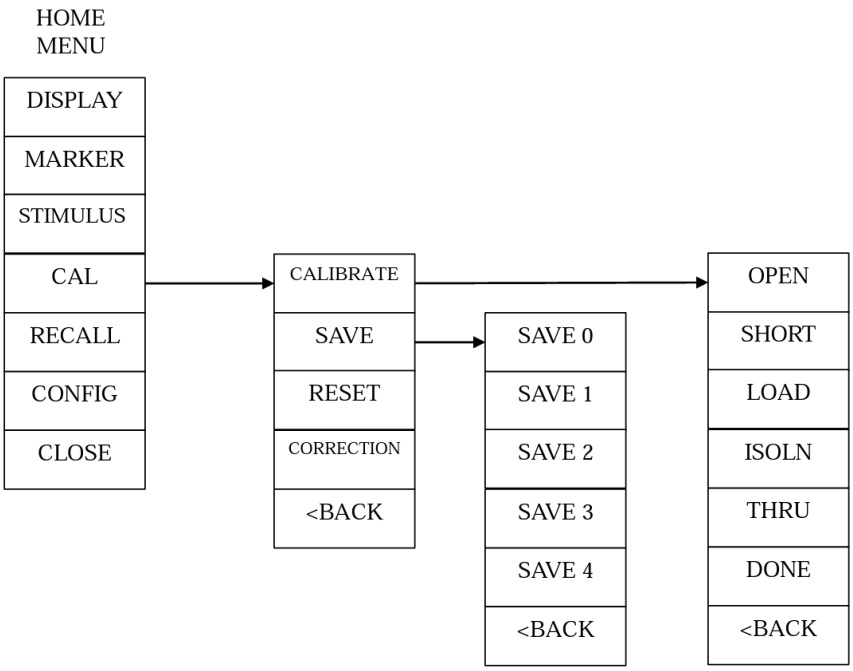


Figure 4: Calibration menu map

Details of the components

The device comprises several essential components that collectively enable the measurement and monitoring of hydration levels. These components work in tandem to capture and record relevant data for analysis and evaluation. Understanding the functionality and purpose of each component is crucial for comprehending the device's capabilities and its role in the research study.

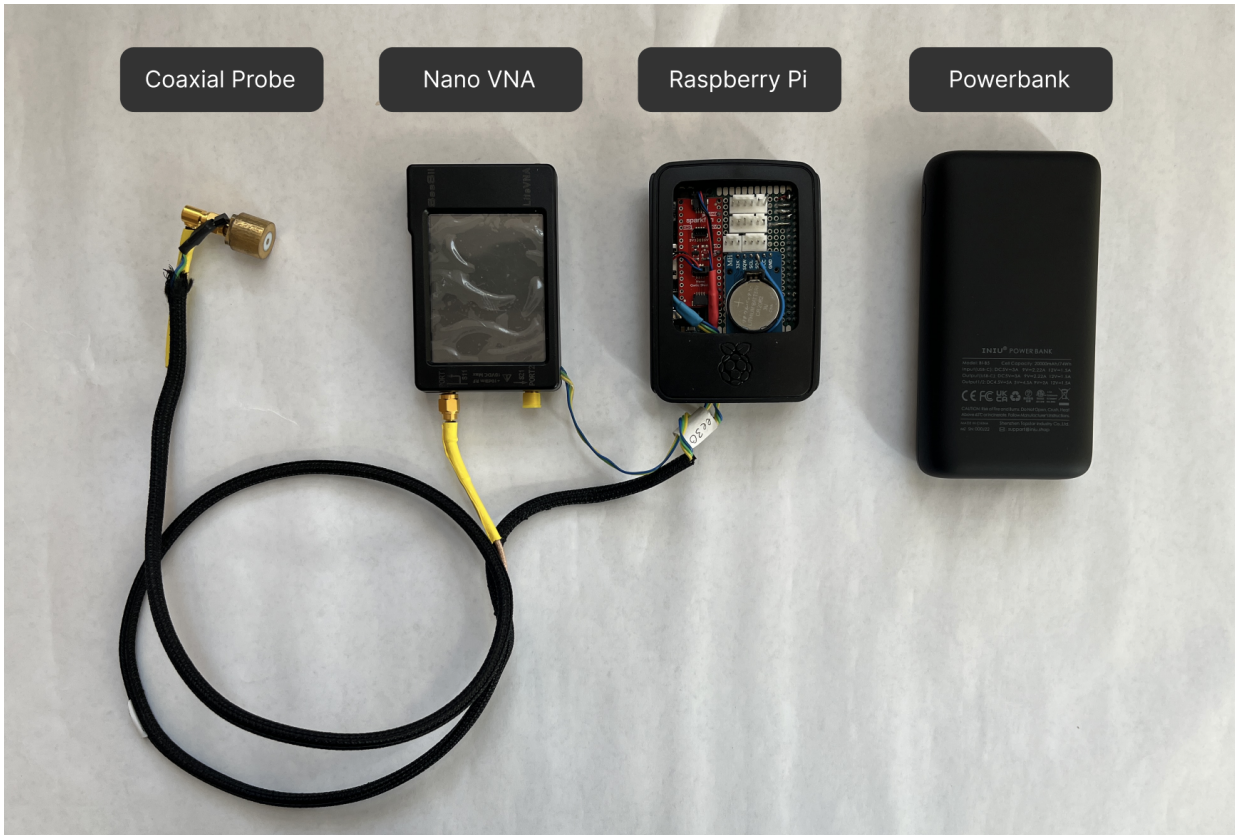


Figure 5: Components of the current device

RF Device Nano VNA, a handheld Vector Network Analyzer

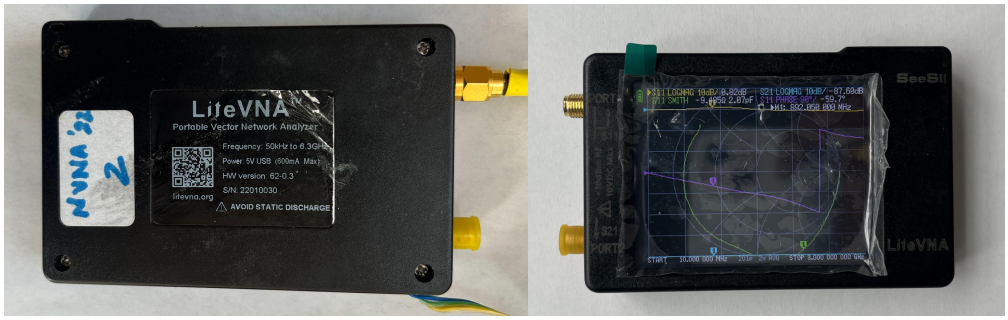


Figure 6: Nano VNA

In this setup, the NanoVNA serves as a radio frequency measurement device, enabling the collection of data through serial communication via a USB connection. It operates within a broad frequency range of 50kHz to 6.3GHz, allowing for comprehensive analysis of radio frequency signals.

Of particular interest in this research is the characterization of signal reflection properties within the frequency range of 2GHz to 4GHz. The focus is primarily on the S11 magnitude parameter, which measures the magnitude of the signal reflection coefficient. The S11

magnitude provides valuable insights into the extent of signal reflection at specific frequencies.

The NanoVNA device provides not only magnitude measurements but also phase information, offering a comprehensive analysis of radio frequency signals. The phase represents the angular component of the complex impedance or reflection coefficient at a specific frequency.

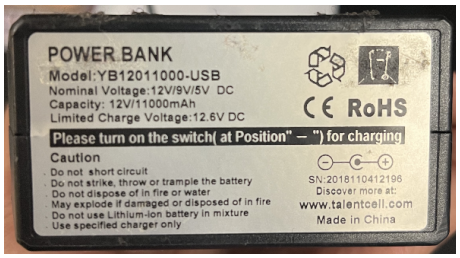
Figure 7: Raspberry Pi model 3

Raspberry Pi 3 Model B, a credit card-sized computer based on the BCM2835 system-on-chip (SoC), includes an ARM11 processor and a powerful GPU.

The Raspberry Pi is utilized to execute the Python library, which facilitates the collection, organization, and analysis of data throughout the experiment. Its versatility and computational capabilities make it an ideal platform for running the necessary software. The Raspberry Pi is connected to several peripheral components, including:

1. Nano VNA: This connection enables the Raspberry Pi to receive and process RF signals, providing valuable insights into signal characteristics and behaviors.
2. Power Bank: To ensure uninterrupted operation, a power bank is connected to the Raspberry Pi.
3. Temperature Sensor: A temperature sensor is connected to the Raspberry Pi, providing real-time temperature readings. This data can be crucial in understanding the influence of temperature variations on the experiment's measurements and overall system performance.
4. Real-Time Clock Module: The Raspberry Pi is equipped with a real-time clock module to maintain accurate timekeeping. This module ensures that the data collected and processed by the Raspberry Pi remains synchronized and organized, even when the device is not connected to the MIT Wi-Fi network.

Power Bank, a 11000 mAH power bank



A higher capacity, 11000 mAH power bank to power the device for a longer duration like 24 hours

Figure 8: Power bank

Coaxial Probe: Open-ended coaxial probe used to measure dielectric properties
Custom made coaxial probe to measure right underneath the skin layer to monitor change in water concentration and correlate it to dehydration. Diameter of the coaxial probe: 8mm

An open-ended coaxial probe consists of a truncated section of a transmission line. The electromagnetic field propagates along the coaxial line and reflection occurs when the electromagnetic field encounters an impedance mismatch between the probe and the tissue sample.

Figure 9: Coaxial probe

Temperature sensors, 18B20 DS18B20 TO-92 3 Pins Wire Digital Thermometer Temperature IC Sensor to collect temperature of the NanoVNA and the body temperature.
Co-axial cables, SMA to SMA connectors to connect the probe to the NanoVNA

Wearable Setup

Design Considerations

We plotted some design considerations that were taken into account before developing the solutions for the wearable setup. Design considerations encompass the important attributes to be considered prior to making significant decisions about the design solution.
Comfort: Given that the setup was intended to be worn by participants throughout the day during human studies, it was essential to ensure a high level of comfort. The setup needed to be designed in a way that participants could wear it comfortably while engaging in their daily activities.

Stability: Considering the limited control over the environment in which participants would be wearing the setup, it was crucial to ensure its stability. The setup had to be constructed in a manner that ensured all components remained securely in place on the body.
Durability: Due to the range of activities participants would be involved in, from sleeping to exercising, the setup had to be durable. The involvement of electronic components necessitated a design that could withstand various activities and maintain its functionality.
Contact with body: Since the primary objective of the wearable setup was to collect data, it was imperative to establish consistent contact between the coaxial probe, sensor, and the participant's body. This ensured reliable data collection throughout the duration of the study.
Reliable data collection: To ensure the reliable collection of data over a 24-hour period, several factors were critical. These included the continuous operation of all components, secure and tight connections, proper enclosure of electronic components, and the implementation of robust data transmission protocols.

Figure 10: Device Components

Wearable parts of the device

The device components, as shown in figure 10, were divided into two main components for the wearable setup as outlined below

1. **Probe attachment to the arm**

Securing the probe on body and to the device: The probe is the only component that sits in contact with the body and collects data continuously.

2. **Device storage on body**

Device: The NanoVNA, Raspberry Pi, and the power bank would be secured on body, to maintain device safety with considerations of how can it be connected to the probe.

Design specifications

To further guide the development of the wearable, some design specifications were drafted informed from previous explorations done in the research lab by other researchers.
Arm wearable: To make the probe not hamper daily activities, an arm-based wearable was suggested to be a potential solution. The probe would also need to be in a position where there wasn't a lot of body hair to make the data collection reliable
Easy to wear: A straightforward way of setting up the wearable on the user to make the human studies efficient and quick.
Minimal weight addition: Since there are a number of components, any added weight to the device would hamper the user experience.
Robust design: The design of the setup should be able to survive daily activities and low-intensity exercises in human studies. The components should ideally not move around a lot to avoid any damage to the electronics and maintain constant data collection.
Easy to repair: Some aspects of modularity in the design would help with the repairability of the setup.

Inspiration for configurations to wear the probe and store the device

The research to find existing solutions for better understanding and inspiration was divided into two parts:

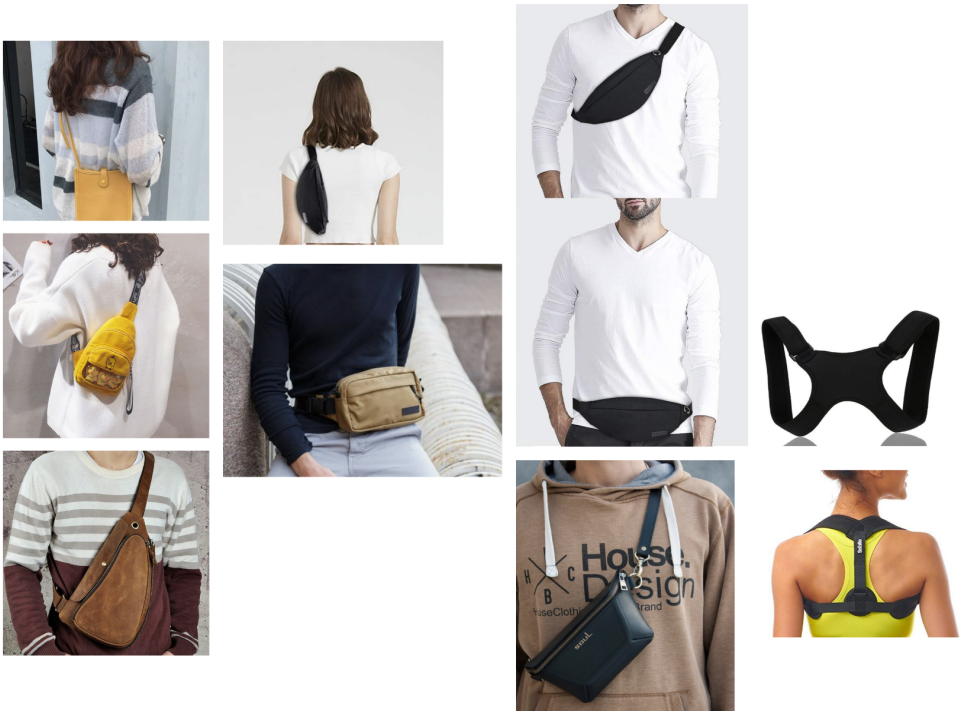


Figure 11: Inspiration for device storage on body

To wear something as heavy as 1.5 kgs for a long period of time:
Some criteria to look for existing products was to find products that could easily be removed like sling bags, cross body bags, shoulder bags. Figure 8 shows an inspiration board with some of the existing products.

Figure 12: Inspiration to wear the sensor on the body

To wear a sensor to be in constant contact with a body part:
Some products that fell into this category were wearables like fitness trackers, wristbands, and products that were attached to the arm, wrist, or ankle.

Ideation to visualize options for the wearable setup

The ideation phase of the process involved brainstorming ideas about how to wear the device while restricting the components moving around. Some of the concepts as shown in Figure 13 outline a configuration of the probe being worn in an armband and the different ways to store the rest of the components.

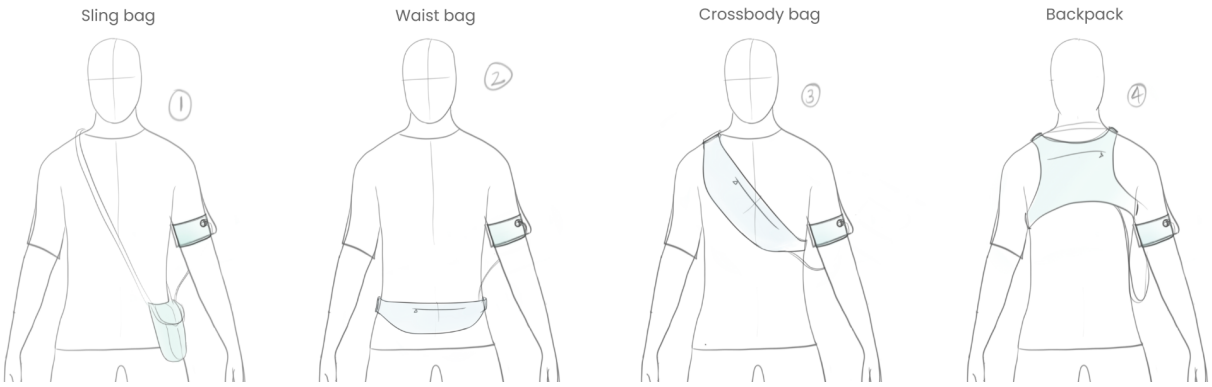


Figure 13: Explorations of ways of carrying the device and the probe

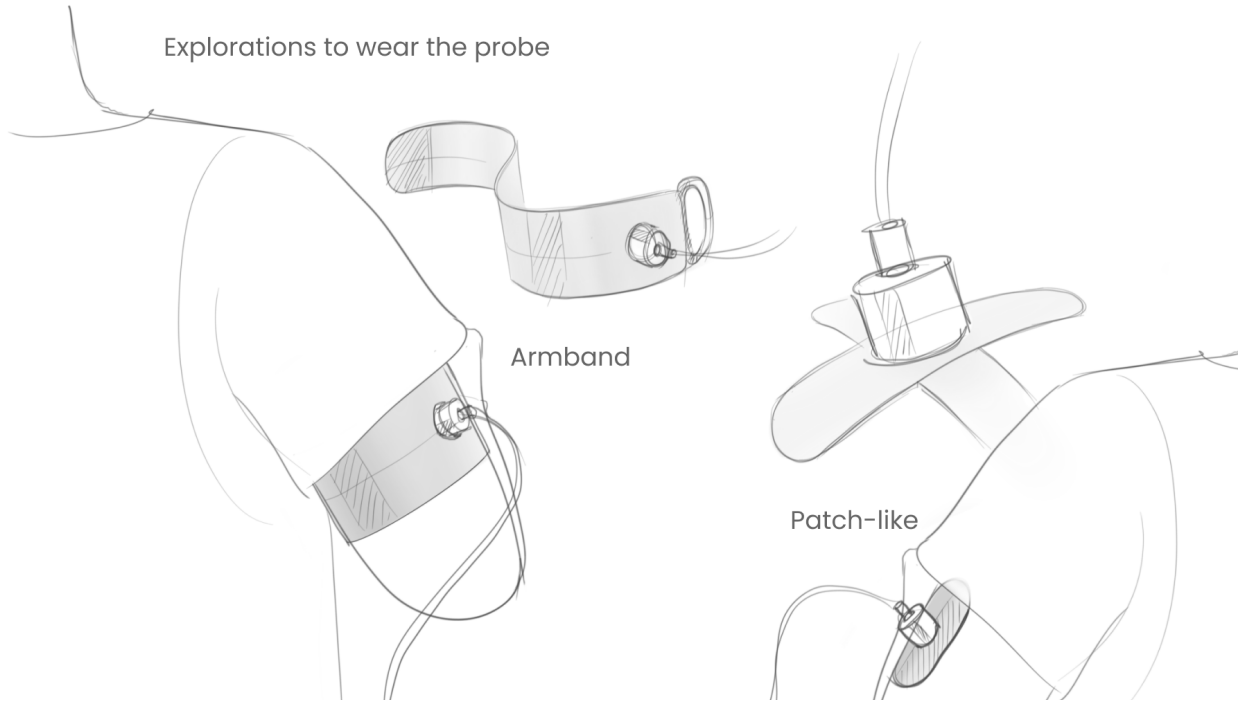


Figure 14: Explorations of ways to wear the probe

Prototypes to test the comfort of different kinds of armbands

Various prototypes were made to test the CAD explorations of the probe sleeve, probe cover, and ways of wearing the setup for a prolonged time. Two ways of wearing the setup on the arm were tested: Armband based setup and a patch-like band-aid-based setup. The armband setup was sturdier to keep the probe in upright position over a period of 8 hours. The patch based setup drooped down because of the weight of the probe over a period of 8 hours.

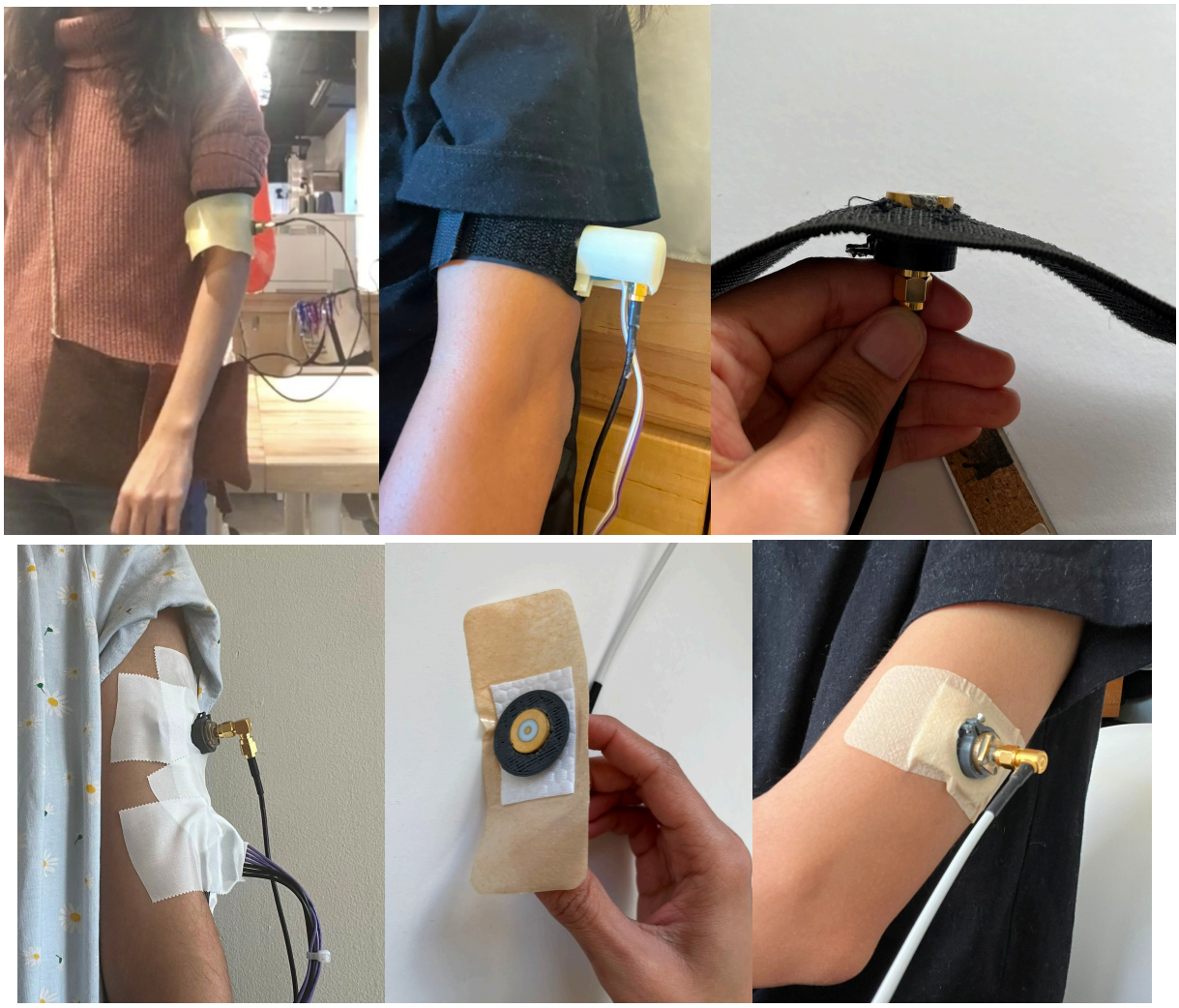


Figure 15: Armband vs bandaid exploration

To make the armband comfortable to wear with minimal movement along the arm, different widths and materials like silicone, textured velcro, cloth-backed velcro, and an elastic band were tested. Cloth-based velcro armbands which were in between a width of 1 inch to 2 inches were observed to be more comfortable than the others and did not move around a lot during longer wear tests. Some of the explorations can be seen in Figure 16.

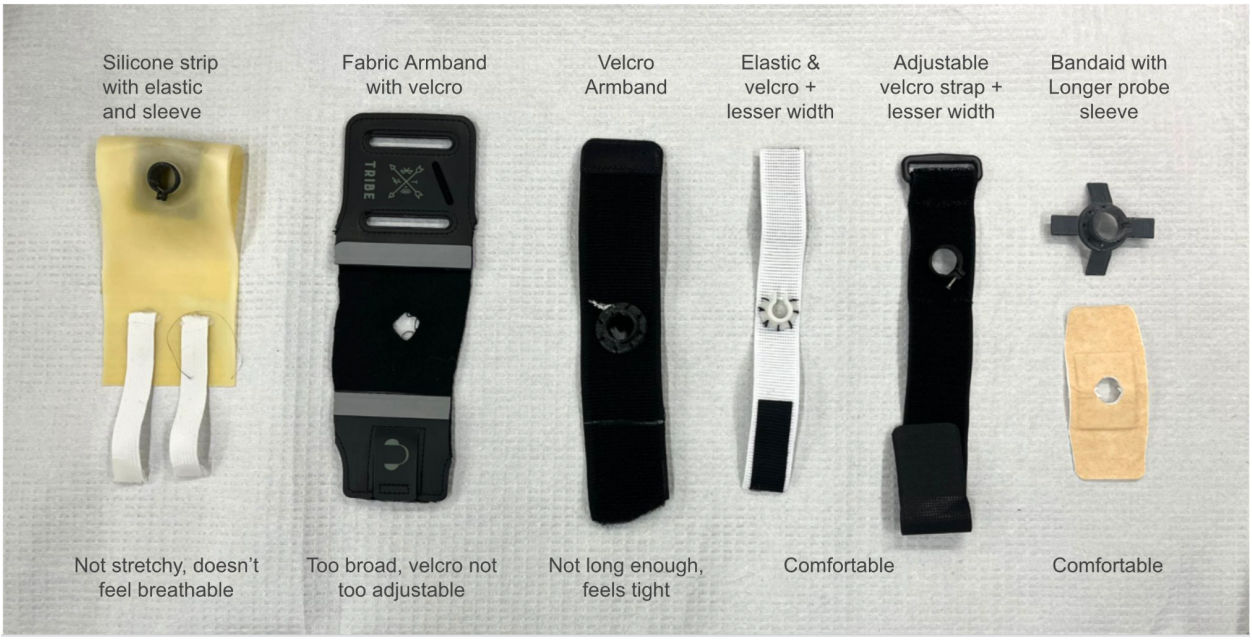


Figure 16: Different widths and materials of armbands

Chosen Configuration

Armband: The probe would be placed in an armband and to further design that, sketches and explorations were conducted to figure out how the probe would be attached to the armband and stay in place. The armband configuration had the following components:

Detachable armband: A velcro-based armband that goes around the arm to secure the probe in place

Probe sleeve: A sleeve that is attached to the armband and in which the probe is placed.

Probe cap: A cover to house the probe and secure it in place.

Waist bag: A waist bag, also known as a fanny pack or cross-body bag, was chosen to store the NanoVNA, Raspberry Pi, and power bank. The versatility of a fanny pack helps to let the user wear it in the orientation they are comfortable with options like wearing it on the waist with the bag facing the front or back, on the shoulder, or across the body.

Probe sleeve and cap explorations

Figure 17 and Figure 18 show explorations of the way in which the probe could be attached to the armband and how it can be cased.

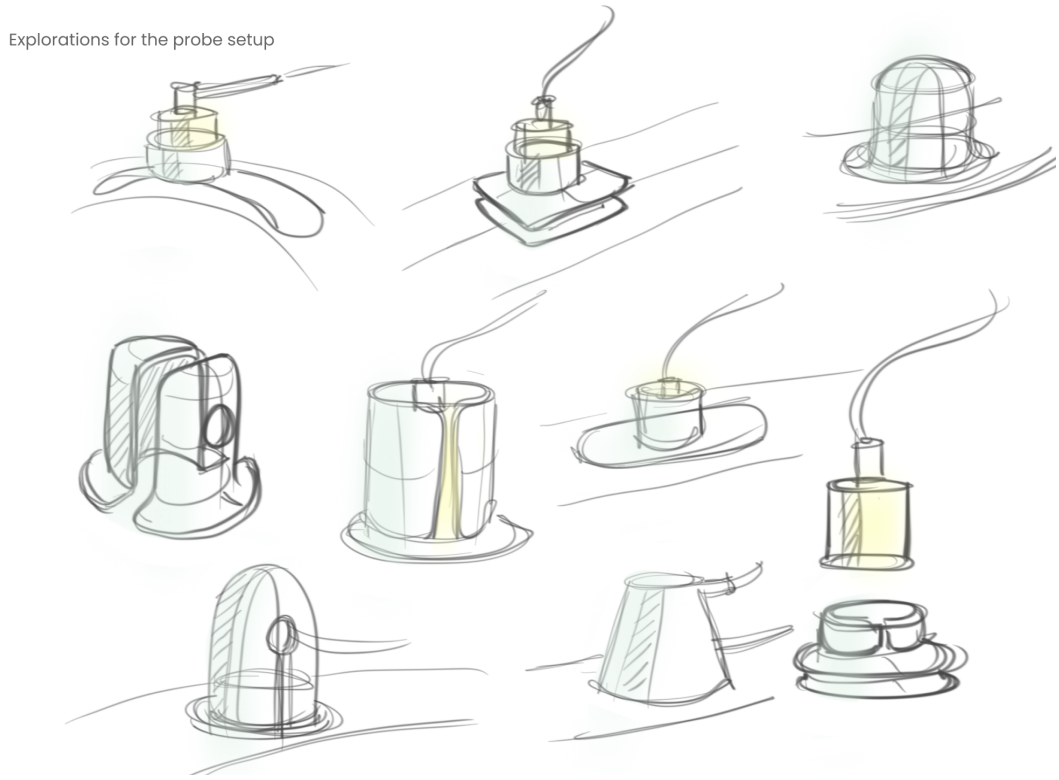


Figure 17: Probe sleeve and probe cap arrangement explorations

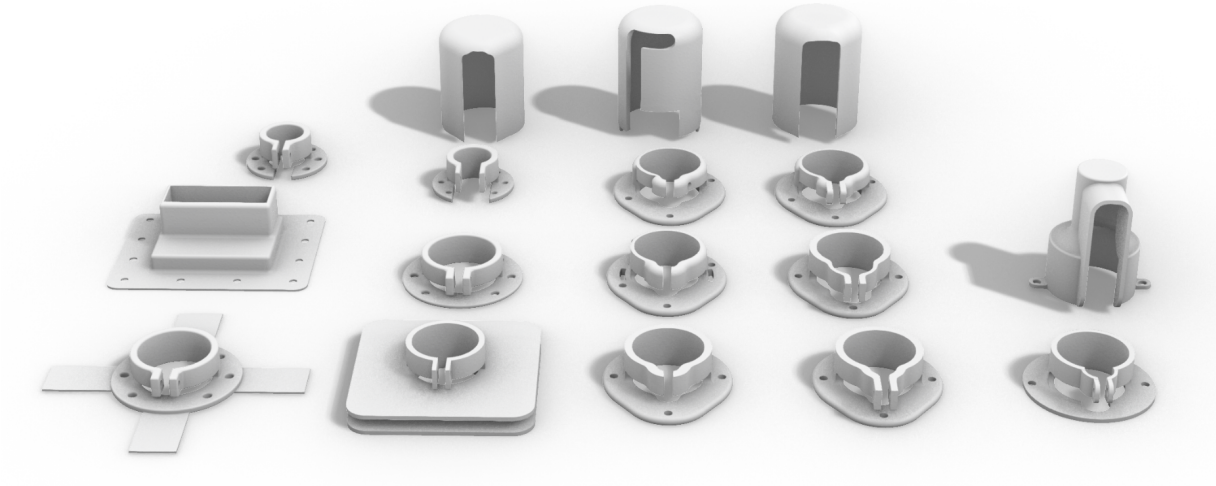


Figure 18: Probe sleeve and probe cap iterations on CAD

In Figure 19, an illustration presents the final arrangement of the probe sleeve, probe cap, and the armband, showcasing the final configuration of these components. To secure their positioning and ensure durability, a sewing technique is employed, connecting the probe cap and probe sleeve through the holes deliberately created in each component.

The act of sewing effectively keeps all the components in place, even during rigorous movements that may occur during human studies. This added stability is vital to maintain accurate and consistent measurements, preventing any unwanted shifting or displacement of the probe sleeve or cap. The sewing technique allows for convenient access to the setup for calibration purposes in between human studies.

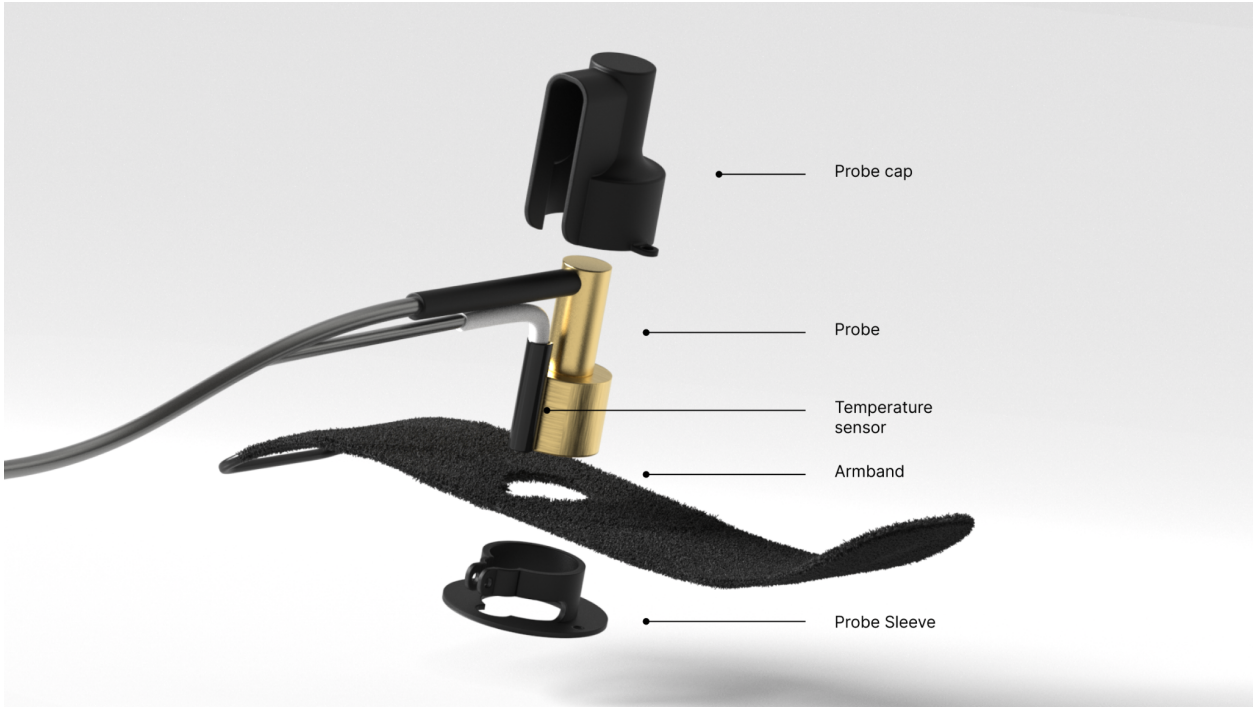


Figure 19: Finalized armband arrangement

The armband is designed with convenience and adjustability in mind. It utilizes a velcro-based fastening system, allowing for easy customization and secure fastening around the participant's arm. This adjustable feature is particularly valuable as it enables individuals with different arm sizes to comfortably wear the armband, ensuring a snug fit for accurate data collection.

To cater to a diverse range of participants, the armband is available in two sizes. This consideration ensures that individuals with different arm circumferences can partake in the study without discomfort or restrictions.

Figure 20: Wearable arrangement

Figure 21: Probe sleeve and probe cap iterations on CAD

The final setup developed for Human studies as shown in Figure 20 and Figure 21 is a wearable device that includes a probe and a temperature sensor placed on the arm covered by a probe cap, secured with an armband. The measurement system is placed in a bag that is worn around the waist. (When sleeping, the bag is placed nearby on the bed.) Wires encased in a flexible sleeve can go under clothing. The measurement system records RF and temperature measurements on an SD card for processing after the study is completed.

Figure 22: Inside the bag and armband setup

In Figure 22, the left picture showcases the bag's design and functionality. The bag is divided into two sections, each serving a specific purpose. The first section is designed to securely hold and protect the Nano VNA and the Raspberry Pi, ensuring their safe encasing. This compartment is backed with padding to prevent any potential damage.

The second section of the bag is dedicated to accommodating the power bank. This section is strategically placed to provide easy access to the power source while keeping it separate from the delicate electronic components in the first section. This segregation helps to maintain a neat and organized arrangement, ensuring that all the necessary equipment is readily available when needed.

In the right picture, the armband arrangement is prominently displayed. This armband serves a functional purpose by securely holding the probes in place during usage. It is designed to comfortably fit around the user's arm, allowing for ease of movement while conducting tests or experiments. The armband ensures that the probes remain in their designated positions, providing accurate and reliable measurements.

Chapter 6: Human Studies

The human studies process included the design of the protocol for COUHES approval to set up a Human Study Procedure, recruit participants, and run Human studies in order to collect data with the help of the wearable device designed. Throughout the process, there were multiple iterations made to the protocol based on the data collected.

Goals for the human studies

- Collect reliable readings for 24 hours in the euhydration cohort and dehydration cohort:
    - Collect and analyze data to observe any physiological changes represented in the studies
    - Visualise data in a readable format to be presented and to pull insights from
    - Compare the Dehydration and Euhydration cohort data
    - Based on the analyzed data, visualize what needs to be done further
- Collect reliable readings for 72 hours in the euhydration cohort and dehydration cohort

Human study Protocol design

Purpose of the study: To determine the performance of a non-invasive experimental hydration status measurement device in detecting physiological changes in healthy individuals. The study was divided into two cohorts: Euhydration cohort and Dehydration cohort. The data from the euhydration cohort would provide information about the normal variations within an individual. The data from the dehydration group will reveal whether the device is sensitive to reduced total body water.

Protocol: 24 hours

Subjects were assigned to the euhydration group or the dehydration group. Those in the euhydration group wore the device for 24 hours, doing what they normally would. Those in the dehydration group were asked to fast, limit their fluid intake, and undertake a cardio exercise of their choice. Otherwise, they could do what they normally would.

Euhydration cohort

Purpose: To get baseline data of dehydration when the participant is wearing the device on a typical day with no limitation on their food and liquid intake.

Hypothesis: The body's hydration levels would not vary a lot since the participant is intaking liquids how they typically would.

Dehydration cohort

Purpose: To get data of dehydration when the participant is wearing the device while fasting for a period of 24 hours.

Hypothesis: The body's hydration levels would vary since the participant is fasting and has limited liquid intake.

Study Protocol (24 hours)

Day 1 morning

Time	Activity
8 am	Report to the lab
8 am - 9 am	Orientation - Discussion of the study and expected actions by subject - Overview of expected and unallowed activities Set up - Probe attached to arm and measurement device in the waist bag. - Adjustments made to ensure comfort. - Weight measured - Activity journal provided, with an example of the kinds of entries requested Group-specific actions - Euhydration group: no additional actions. Participants can eat, drink, and exercise as they would on any typical day. - Dehydration group: subject provided with an 8-ounce bottle of water. The subject asked not to eat and to drink no more than 8 ounces of water during the 24 hour study.
9 am	Subject leaves lab
During the	Euhydration group: Normal daily activities; noted in the activity log.

day	Dehydration group: - Cardio exercise of their choosing. - Note exercise and other activities in the activity log - If possible, subjects should weigh themselves before and after the exercise on the same scale. - Subjects are told that they may find it easiest to exercise early in the study when they are least dehydrated.
Before sleeping	- If possible, the subject weighs themselves before going to bed. - Remove the bag from the waist and position nearby on the bed - Note the weight and the time going to bed in the activity journal

Day 2 morning (handoff day)

Time	**Activity**
After waking up	- Reposition bag on the waist - If possible, the subject weighs themselves after voiding urine. - Note the weight and the time of waking in the activity journal.
8:00 am - 8:30 am	Return to the lab - Weight measured - Device removed - Activity log collected - Complete post-study questionnaire

After some initial tests in the 24-hour cohorts, another protocol was designed for 72 hours to collect hydration data over multiple days.

Protocol: 72 hours

Subjects were assigned to the euhydration group or the dehydration group. Those in the euhydration group wore the device for 72 hours, doing what they normally would. Those in the dehydration group were asked to fast, limit their fluid intake, and undertake a cardio exercise of their choice for 24 hours on day 2. Otherwise, they could do what they normally would.

Euhydration cohort

Purpose: To get baseline data of dehydration when the participant is wearing the device over a period of three typical days with no limitation on their food and liquid intake.

Hypothesis: The body's hydration levels would not vary a lot since the participant is intaking liquids how they typically would.

Dehydration cohort

Purpose: To get data of dehydration when the participant is wearing the device for three days while fasting for a period of 24 hours on day 2.

Hypothesis: The body's hydration levels would vary on day 2 as compared to Day 1 and Day 3 since the participant is fasting and has limited liquid intake.

Study Protocol (72 hours)

Day 1 morning

Time *(example)*	**Activity**
Within two hours of waking up, ideally 8 am	Report to the lab
8 am - 9 am	Orientation - Discussion of the study and expected actions by subject - Overview of expected and unallowed activities Set up - Probe attached to arm and measurement device in waist bag. - Adjustments made to ensure comfort. - Weight recorded - Activity journal provided, with an example of the kinds of entries requested - Participant provided with a power bank for switching power banks before going to bed in the night - The participant will be provided with an 8-ounce bottle of water. The participant will be asked not to eat and to drink no more than 8 ounces of water during the Day 2 of the study for 24 hours.

9 am	The participant can leave for the day.
During the day	- Normal daily activities; noted in activity log.
Rest of the day	Go on with their daily routine.
Before sleeping	- If possible, weigh themselves before going to bed. - Replace the Power bank in the device with the spare power bank - Remove the bag from the waist and position nearby on the bed - Note the weight and the time going to bed in the activity journal

Day 2 morning

Time	**Activity**
After waking up	- Reposition bag on waist - If possible, the subject weighs themselves after voiding urine. - Note the weight and the time of waking in the activity journal.
During the day	Euhydration Cohort: - Normal daily activities and eating routine; noted in the activity log. Dehydration cohort: - Eat a meal in the morning before starting to fast. - Weigh themselves after the meal - Fast and limit liquid intake to no more than 8 ounces of water for the next 24 hours. - Cardio exercise of their choosing. - Note exercise and other activities in the activity log - If possible, subjects should weigh themselves before and after the exercise on the same scale. - Subjects are told that they may find it easiest to exercise early in the day when they are least dehydrated.
Before sleeping	- If possible, the subject weighs themselves before going to bed. - Replace the Power bank with the spare power bank - Remove the bag from the waist and position nearby on the bed - Note the weight and the time going to bed in the activity journal

Day 3 morning

Time	Activity
After waking up	- Reposition bag on waist - If possible, the subject weighs themselves after voiding urine. - Note the weight and the time of waking in the activity journal.
During the day	Normal daily activities and eating routine; noted in the activity log.
Before sleeping	- If possible, the subject weighs themselves before going to bed. - Replace the Power bank with the spare power bank - Remove the bag from the waist and position nearby on the bed - Note the weight and the time going to bed in the activity journal

Day 4 morning (handoff day)

Time	Activity
After waking up	- Reposition bag on waist - If possible, weigh themselves after voiding urine. - Note the weight and the time of waking in the activity journal.
8:00 am - 8:30 am	Return to the lab - Weight taken - Device removed - Activity log collected - Complete post-study questionnaire

Types of activities permitted throughout the study:

- Low-intensity chores at home like cleaning, cooking, laundry.
- Desk work, attending classes/ office work.
- Daily activities like using the restroom.
- Traveling in public transport, driving a car, biking etc.
- Sleeping with the armband on (the participant was advised about the best way to orient the device while sleeping).
- Regular exercises, so long as they are ones where the participant feels the probe can remain in place throughout.

Activities NOT to be conducted during the study:

- Bathing: To avoid any contact of the electronic setup with water.
- Swimming: To avoid any contact of the electronic setup with water.
- Any activity that would make the bag and armband come in contact with water.

- Any activity that clearly could lead to pulling on or dislodging the probe and wire.
- Any activity that would require the participant to disconnect the probe (for example if the participant prefers the wire to be worn over their clothing and the participant cannot remove clothing without disconnecting the probe, then please wear the clothing until the conclusion of the study).

Sleep: Device placement

- We ask that the participant wears the armband while sleeping.
- The waist bag should be removed and placed either next to the participant's head or on a close-by nightstand.
- The bag should be placed in a way that the participant does not move it unintentionally while sleeping and that it doesn't fall if placed on the nightstand.

Ideal Participants

Individuals who are healthy, preferably comfortable with some cardio exercise, BMI between 18–27%, and between 18 and 45 years old. They should not have any heart conditions, diabetes, kidney conditions or any other significant medical condition that would normally prevent them from performing physical activity.
Inclusion Criteria for Dehydration Group: Comfort with some cardio exercising.

Recruitment Process

Subjects were recruited by word of mouth, email, social media, and advertising posters around MIT.
The prescreening questionnaire was circulated to recruit eligible participants on the basis of the inclusion and exclusion criteria. A call was organized with the eligible participants to verify their responses and to go over the consent form and its different sections. Their responses of the pre-screening questionnaire were verified with the subject before the consent was signed. A time and date were chosen through Calendly as per the participant's availability to conduct the study. On the day of the study, the consent form was signed before starting the activities.

The Recruitment Poster

The recruitment poster shown in Figure 23 was helpful to give a glimpse of the study and get participants interested in being a part of the study. This poster was circulated on Whatsapp groups, slack groups, and was put up in the infinity corridor, elevators, dorms, and advertisement boards around campus.

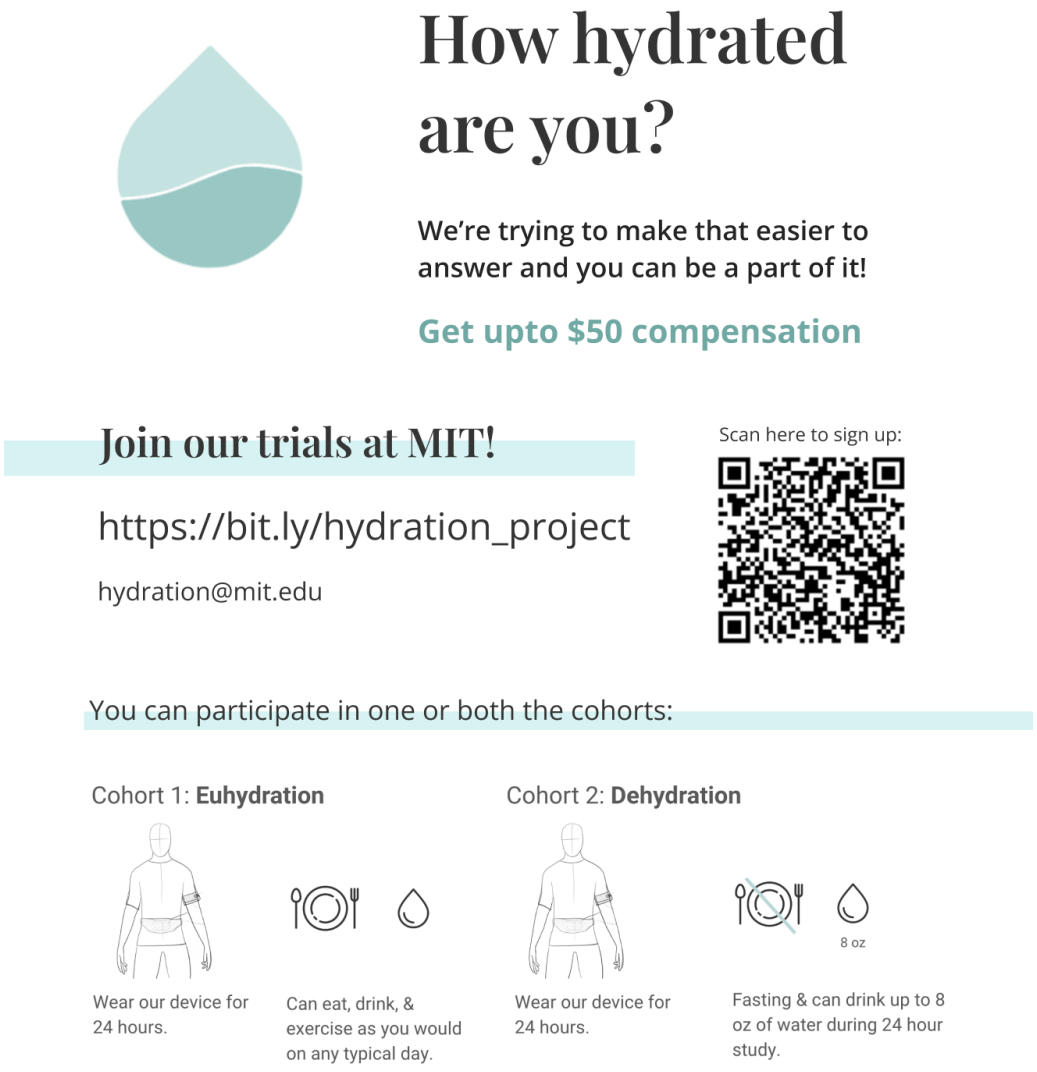


Figure 23: Recruitment poster used to advertise participation in study

Pre-Screening Questionnaire

Introduction: Our project at MIT aims to develop a simple and non-invasive hydration monitor for clinical and non-clinical use, that simplifies hydration monitoring and enables improved hydration management for self-care and the care of others. This study is part of a broader project aiming to develop and test a novel non-invasive hydration monitoring device.

The study will be 24 hours long and you will be wearing a device that consists of a small probe attached to an armband, attached by wires to a device box, and a battery placed in a fanny pack. You will be assigned to one of these two groups. (If you have a strong preference to be in a particular group, you may request it.)

Cohort 1, Euhydration group: Go about your daily activities while wearing the device, participants will be compensated with $30 amazon gift cards or checks
Cohort 2, Dehydration group: Fasting for 24 hours with limited intake of water along with some exercising while wearing the device, participants will be compensated with $50 amazon gift cards or checks

Who Can Participate?

Anyone in the age range of 18-45 years
Those who have BMI between 18-27 %
Those who can wear a device on their body for 24 hours
Those able to attend 30 min study visits in E25 at the beginning and end of the study
Those who do not have any heart conditions, diabetes, kidney conditions or any other significant medical condition that would normally prevent them from performing physical activity.

1. E-mail address
2. Are you between 18-45 years old? (Yes/No)
3. Assigned gender at birth: Female/Male/Other(text box)
4. Is your BMI between 18-27? (Yes/No)
5. Are you available to wear a device and conduct daily activities for 24 hours? (Yes/No)
6. Are you willing to fast for 24 hours?
7. Are you willing to limit water intake to 8 ounces (0.2L)?
8. Are you willing to come to building E25 or another building on MIT campus at the beginning and end of the study?

Medical History:

9. Would you describe yourself as being healthy?
10. Do you have any medical condition that may restrict you from participating in the study? (Yes/No)
    Have you been diagnosed with any of the following conditions which might restrict exercising? (If the answer is yes to any of these, you will not be eligible to participate in the cohort 2: Dehydration study)
    a. Uncontrolled angina/ chest pain (Yes/ No)
    b. Diabetes (Yes/ No)
    c. Kidney conditions (Yes/ No)
    d. Arrhythmias (Yes/ No)
    e. Acute systemic infection (i.e., fever, body ache, swollen lymph nodes, etc) (Yes/ No)
    f. Implantable cardiac devices (Yes/ No)

g. Recent heart attack (Yes/ No)
h. Severe congestive heart failure (Yes/ No)
i. Congestive Heart Failure (CHF) (Yes/ No)
j. Significant cardiovascular disease such as coronary heart disease (Yes/ No)
k. Hypertension (high blood pressure) (Yes/ No)
l. Hypotension (low blood pressure) (Yes/ No)
m. Postural Hypotension (feeling lightheaded with quick change in position) (Yes/ No)
n. Any medications for the above conditions (Yes/ No)
o. Pregnant or planning on getting pregnant (Yes/ No)

Exercise details

11. What exercises (if any) do you regularly perform?
12. How often do you routinely participate in aerobic exercise?
    a. Rarely
    b. 1-2 times a week
    c. 2-3 times a week
    d. 3-5 times a week
    e. 5 or more times a week
    f. Other
13. Are you willing to conduct a cardio exercise for as long as you normally do while wearing the device?

Data Collection and Storage

Subjects were assigned an ID which was recorded along with any other identifying factors in a password-protected spreadsheet. All other data were linked to this ID in spreadsheet form and the RF data is stored in secure anonymized folder structures by the team. We utilized Office of General Council (OGC) approved REDCap forms provided by CCTR for the recruitment, pre-study questionnaires, and post-study questionnaires. Prior to the consent visit, eligible participants were emailed the COUHES-approved study consent form for their review. Web-based HIPAA-compliant and secure REDCap database for consenting and data storage were used for ICP consenting and storage of consent forms.

Human Study Procedure Guiding Checklist

During the Human study process, an activity checklist was set up to follow the same procedure from the setup till the end of the human study as shown in Figure 21.

Tighten all connctions	Power bank switched on	Consent	Details about exercising	Details about Weight before and after sleeping	Details about switching the power bank before sleeping	Mail/ address details for compensation	Small notebook given to the person, explained about documentation	Mark armband location	Weight Day 1 (Kg)	Participant's Jacket fits on the probe	Time of device starting	Time of wearing device	Test end time	Weight after wearing device (Day 1) (kg)	Weight before sleeping (Kg) - don't move - keep it at the same place	Weight after waking up - after voiding urine	Weight Day 2 /last day (Kg)
☑	☑	☑	☑	☑	☐	☑	☑	☑	☑	☑	10:12 AM	11:30	11:10 AM	67.90	65.40802	64.18332	65.50
☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑		9:30	10:30 AM	52.10	52.75	51.55	51.00
☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	10:30 AM	1:25 PM	3:00 PM	66.90	65.40802	64.8637	65.50
☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	8:45	9:28	10:30 AM	50.10	48.95	48.45	50.20
☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	8:45	9:24	10:00 AM	81.60	81.45	81.15	79.80
☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	7:45	9:30	10:00 AM	90.00	88.6	87.55	87.70
☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☐	9:00 AM	10:40	6:10 PM	78.20	80	79.5	79.50

Figure 24: Activity checklist for the whole human study procedure

The steps were categorized under four main sections:

1. **Study Details**

    a. Participant code: Code for differentiation between the two cohorts and the serial number of the study. E1 would be the first 24-hour Euhydration study, D1 would be the first 24-hour Dehydration study, MD5 would be a dehydration study in the 72-hour cohort, and ME5 would be a dehydration study in the 72-hour cohort.
    b. CCR ID Group: The unique Identification code assigned on the RedCap platform
    c. Date: Date of the start of study

2. **Communication with the participant for scheduling and consent signing process**

a. Calendly Link: After a participant fills in the prescreening survey on Redcap, the answers are checked to see if the inclusion criteria are met. If the participant meets the inclusion criteria, it is marked so in the RedCap form also named as 'Meets Inclusion Exclusion Criteria' which triggers a form being sent to the participant with a calendly link for them to choose a suitable day and time to start the study.
b. Intro to the study mail (after sign-up on Calendly): An email is sent with brief details of the cohort activities along with an attached consent form on the day the participant schedules the study through the Calendly link. The mail reads as follows:

Thank you for signing up for the Hydration study and for scheduling a slot! I'm reaching out to confirm the study details and address any questions you would have. Please let us know in advance if a change in time/day for the study would be preferred so that we can accommodate a switch.

Please find attached the consent form for your reference. We will be going over the same on [Date and time] and the consent will also be signed then.
You have opted in for the **Dehydration cohort** where you will be:

- Fasting for 24 hours starting Tuesday morning and limiting water intake to 8 ounces (a bottle for the same will be provided).
- Wearing the device for 72 hours starting Monday: waist bag connected to an armband as shown in the picture attached. The probe is what will be capturing the hydration data.
- Compensation of $50 is provided for the dehydration study.

If you would not want to fast, we can move you to the **Euhydration cohort** where you would just be wearing the device and going through your daily activity.

- The location of the lab is E25-413, if you have any trouble finding the location, you can reach out to me by mail, or on [phone number] (text, WhatsApp, iMessage available)

Please feel free to reach out with any questions or concerns.

c. Reminder mail about the study (1 day before the start of the study): A mail details like study time, location, and some directions is sent a day before the study to reduce the number of no-shows or end moment cancellations. The mail reads something like:

We wanted to reach out with some recommendations to make the study smoother tomorrow:

- If possible, we recommend that you wear a **half-sleeved t-shirt** as the base layer so you can easily wear the armband as shown in the image attached.
- The study duration is 72 hours with the device worn throughout the study and with 24 hours of fasting.
- **We recommend that you hydrate well enough today and tomorrow. Your fasting period is recommended to start at 10 am Tuesday**
- Since the armband is recommended to not be removed for the first 24 hours, we advise participants to shower before the start of the study.
- The location of the lab is E25-413 (The building next to MIT Medical), if you have any trouble finding the location, you can reach out to me by mail, or by [phone number] (text, WhatsApp, iMessage - anything works)

Please feel free to reach out with any questions or concerns you might have.

d. Consent signing: On the day of the study, a go-through of each section of the consent form is done before the participant signs the consent form on the Redcap portal. During the go-through of the consent form, details of the protocol, details of the activities to be done, and activities not to be done are discussed, and any questions the participant has answered. Some of the details included in the checklist from the protocol are as follows:
    i. Details about exercising: Checked after details about exercising have been shared.
    ii. Details about Weight before and after sleeping: Checked after details about weight collection have been shared.
    iii. Details about switching the power bank before sleeping: Since the current power bank runs for 24 hours, the participant is asked to switch them with a spare one provided at the start of the study. In the 72 hours study, a charger is also provided for them to charge the power bank not in use at the time.
    iv. Small notebook given to the person, explained about documentation: Throughout the study the participant is asked to log their activities and at the time at they were conducted, food and liquid intake, and any adjustments done either the probe or the device.
    v. Weight measurement before sleeping: The participant is asked if they own a weighing machine to measure their weight before sleeping and after waking up. If they don't own a machine, a spare one from the lab is provided to them.
e. Mail/ address details for compensation: If the participant is not a US citizen, a VPF compensation form is filled for them to receive the compensation by a check with a 30% tax deduction. If they are a US citizen an amazon gift card is sent to them to their desired amazon account.

3. Setup of the device

a. Make sure both the power banks are charged fully
b. On device calibration to check fluctuations: Calibrate on the NanoVNA directly and move the cable with the probe attached around to check any major fluctuations in the screen. While moving the cable around, one main consideration is to move the cable from the two attachment points, near the nanoVNA and near the probe. If the wire is broken, the s11 reading on the screen will go to 2 or above.
c. Calibration: atleast 3 hours before the study, calibrate the NanoVNA following the calibration process outlined in chapter 2.

d. SD card memory check: Check if enough memory is available in the SD card, a 24 hour study generally taked upto 400mb if memory storage.
e. Correct file number and calibration file number in the memory card: .json file, Run script: The .json file andcailbration folder is setup in the memory card as outlined in Chapter 2, Software setup.
f. Tighten all connections: All the connections are checked to be tight enough
g. Power bank switched on: The device is setup to collect data two hours before the study start time to let the device reach a constant temperature.

4. **Data collection during the study**

a. Time of device starting: The time at which the device was switched on before the study.
b. Time of wearing device: The time at which the person wore the armband.
c. Weight after wearing device (Day 1) at the start of the sudy.
d. Weight before sleeping: Weight is captured how many ever nights the person has the device on.
e. Weight after waking up - after voiding urine: Weight is captured how many ever nights the person has the device on.
f. Weight Day 2 /last day (kg): Weight before removing the device at the end of the study
g. File Name: Name of the .json file in the github folder
h. Data - Folder Name under which the data is stored
i. Activities list: What were the activities logged in the journal
j. Notes: Any other information shared by the participant or observations made.
k. Takeaways for next study: Learnings, obstacles or changes needed for the next study.

Post-Study Questionnaire

Euhydration group

1. Did you have to remove the armband at any point of time? - Yes/No, (if yes)-
    a. At what time did you have to remove the device?
    b. For how long was the device removed?
2. Is there any activity that you were not able to record in the activity log and that you would like to share here? (Description/No)

Dehydration group

1. Did you have to remove the armband at any point of time? - Yes/No, (if yes)-
    a. At what time did you have to remove the device?
    b. For how long was the device removed?
2. Did you drink more than the assigned water at any time in the day? If yes-
    a. At what time did you drink water?
    b. How much water do you think you drank?
3. Did you eat at any time during the day? If yes-
    a. At what time did you drink water or eat?
    b. What did you eat and approximate quantity
4. Is there any activity that you were not able to record in the activity log and would like to share here? (Description/No)

Types of challenges in the human studies

The human study was also filled with unexpected challenges which needed either iterations to the device or iterations to the protocol. Some of the challenges have been outlined in the table 1 below:

Study Number	Problem	Cause	Solution
D2	Study ended before 24 hours	Power bank ran out of battery	Switch power bank before sleeping or within 23 hours
D4	S11 magnitude fluctuations upto +6	Coaxial probe cable broke giving rise to fluctuations in data	Heat shrink on the cable ends and additional calibration step directly on the NanoVNA
D10	Power bank on but the nanoVNA and Raspberry pi were switched off during the study	Power bank to Raspberry wire broke	1. Manual inspection of cables before the study starts 2. Direct participant to check if the nanoVNA is on or not during the power bank switch
E1, E2, E3	Unsurity of the euhydration study's validity	Participant didn't drink enough water during the Euhydration study	

D3	Data doesn't qualify to be in either cohort	Participant broke fast during the dehydration study	Ask the participant to keep a note of when they break the fast and what they consume
D8, D9,	No way to correlate the dehydration readings with	Participant wasn't able to measure weight at the start and end of the fasting in studies longer than 24 hours	Direction to start and end the fast when a weighing machine is accessible
D6	The readings would differ as the location on body has changed	Participant changed the arm on which probe was placed during the study	Clear communication during onboarding

Table 1: List of challenges faced in the human studies

Mean and Standard Deviation of the S11 studies

Table 2 presents the average and standard deviation for each conducted human study. These values were derived from the S11 magnitude values of each study in the time period the device was on body for each participant. It helps to analyze the data to identify similarities, differences, and trends in the S11 magnitude across the conducted studies. The study with the most fluctuation was D4 because of a broken wire, as seen in the table 2, the standard deviation is 3.5

Study Number	Mean of the s11 magnitude (dB)	Standard Deviation	Comments
E1	-2.75	0.06	Stable data
E2	-2.64	0.44	Stable data for the most part, probe got disconnected by the end of the study
E3	-2.69	0.069	Stable data
E4	-2.735	0.0477	Stable data
D1	-2.75	0.075	Data fluctuation while sleeping: nano VNA heated up till 80 degree C due to low ventilation in the bag
D2	-2.57	0.079	Stable data
D3	-2.93	0.32	Fluctuations due to broken cable

D4	-0.29	3.5	Fluctuations due to broken cable
D5	-2.715	0.47	Stable data
D6	-2.49	0.7	Stable data
MD7	-2.65	0.09	Stable data but power bank switched off by participant by mistake
MD8	-2.8	0.057	Stable data
MD9	-2.63	0.077	Stable data
MD11	-2.62	0.35	Stable data

Table 2: Mean and standard deviation of the S11 magnitude of the human studies conducted

Chapter 7: Data Visualization

The data visualization chapter focuses on presenting and analyzing the data collected during the human studies. A combination of Excel and Figma, a graphic design tool, was utilized to convey the findings. These tools allowed for the creation of various formats and templates that best captured the essence of the collected data and facilitated clear and understandable visual representations. Different visualization techniques were employed to explore and communicate the findings effectively. The selected formats and templates were carefully designed to enhance the readability and clarity of the data, ensuring that the key aspects and significant observations were highlighted.

Goal

To design a method for clear visualization of the change in hydration against the time and temperature.

Data collected during the human study

During the human studies, the following data was collected:

1. NanoVNA Temperature: The temperature of the NanoVNA device was captured using a dedicated temperature sensor positioned on the NanoVNA itself. This allowed for monitoring any fluctuations in temperature during the study.
2. Probe Temperature: The temperature in the vicinity of the probe was measured using an additional temperature sensor placed adjacent to the probe. This enabled the assessment of temperature variations in close proximity to the sensor.
3. S11 Magnitude and Hydration Estimates: The readings from the NanoVNA were utilized to collect data on the S11 magnitude, which represents the signal reflection coefficient, as well as the corresponding hydration estimates. These measurements provided insights into the hydration levels of the participants.
4. Time and Date Tracking: To ensure accurate time synchronization and record keeping, a real-time clock unit was integrated with the Raspberry Pi. This component facilitated the precise tracking of the study's duration and allowed for the proper chronological organization of the collected data.
5. Activity Log: An activity log was maintained by the participants to document the activities conducted by the participants throughout the study duration. This log captured important details regarding the specific actions, exercises, or movements performed, providing context to the collected data and aiding in the analysis process.

By collecting this comprehensive dataset, encompassing temperature measurements, S11 magnitude, hydration estimates, time and date records, and activity logs, the research team gained valuable insights into the dynamics of hydration and its relationship with various factors. The data served as a foundation for subsequent analysis, interpretation, and evaluation, ultimately contributing to a deeper understanding of the study's objectives and outcomes.

Data Visualization

The final iteration of the visualizations comprised two distinct graphs, each serving a specific purpose in depicting the collected data. The first graph illustrated the relationship between the S11 magnitude, temperatures, and time. This graph provided a comprehensive overview of how these variables varied over the course of the study, enabling a holistic understanding of their interplay.

The second graph focused on capturing the percentage change in hydration level, derived through the temperature correction of the S11 magnitude data. By incorporating the temperature correction to the s11 magnitude graph, this graph effectively showcased the changes in hydration levels and provided valuable insights into the dynamics of hydration throughout the study period.

Together, these two graphs offered a comprehensive visual representation of the collected data, allowing for a clear and concise understanding of the relationships and patterns between the S11 magnitude, temperatures, hydration levels, and time. The visualizations served as powerful tools in facilitating data analysis, interpretation, and communication, ultimately enhancing the overall understanding of the study's findings and contributing to further decision-making.

Figure 25 displays the plot depicting the variation of S11 magnitude and temperature over time in the study duration. To facilitate a more comprehensive analysis of the data, the graph incorporates an overlay of the activities performed by the participants during the study duration. These activities have been seamlessly integrated into the Excel graph output using the Figma platform. This visualization approach to incorporate the activities visually has proven beneficial in establishing correlations between specific activities and observed fluctuations or irregularities in the data.

By including the activity overlay, valuable insights can be observed about how participant actions relate to the recorded measurements. This approach has facilitated the identification of patterns and trends, enabling a more in-depth understanding of the data collected throughout the human studies. This graph stands as a significant output, contributing to the overall findings and conclusions drawn from the study.

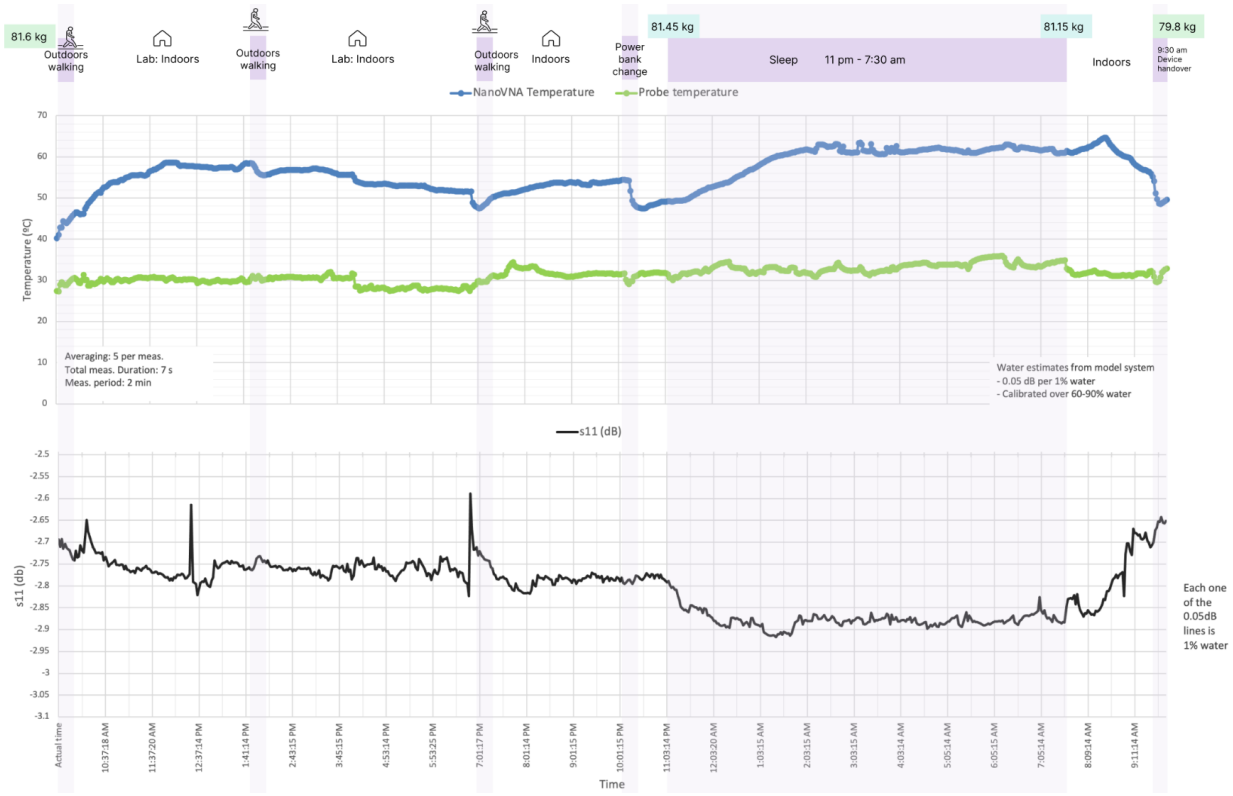


Figure 25: Plot showing the S11 magnitude and temperature changes over time in a human study. The graph also includes the participant's activity log details overlaid on it. It provides a representative visualization that showcases the fluctuations in the S11 magnitude.

In order to address the observed inverse relationship between NanoVNA readings and NanoVNA temperature, a correction method was developed to obtain accurate hydration estimates. Incubator tests were conducted to explore the correlation between temperature variations of the probe and NanoVNA and their impact on NanoVNA readings.

The incubator test involved setting up two separate incubators: one containing the NanoVNA with a temperature sensor, and the other containing the coaxial cable with a load of 70 ohms attached, also equipped with a temperature sensor while the raspberry pi sits outside in the ambient temperature. The temperatures in both incubators were carefully controlled. The experiment involved maintaining a constant temperature for a period of time, followed by a gradual increase in temperature over several hours first in the NanoVNA incubator and then in the Probe incubator. This allowed for the recording of variations in the s11 magnitude under different temperature scenarios.

The data obtained from the incubator study was then used to establish the relationship between the change in probe/NanoVNA temperature and the corresponding change in

readings. This relationship enabled the determination of values for Device correction and Probe correction.

Temperature is corrected with a first-order linear model such that:

$$W_{corr}(t) = W_{raw}(t) + \sum_i C_i \cdot \Delta T_i(t)$$

t: time

W_corr: corrected water concentration

W_raw: calculated water concentration

ΔT_i: change in temperature i since first measurement (T_i(t) - T_i(0))

C_i: slope of water concentration/a temperature (subject's/measurement device/environment) from previous experiments

The collected data from the human study is then subjected to low-pass filtering in order to apply the corrections derived from the incubator test. This temperature correction process was applied to generate a temperature-corrected plot, enhancing the accuracy of the hydration estimates obtained from the human study data.

Figure 26 showcases a plot displaying the change in hydration against the time and duration of the study. This plot represents the corrected percentage change in hydration in blue, accounting for the influence of temperature fluctuations. To provide a better understanding of the data, the graph also includes an overlay of participant activities. Similar plots were created for all the studies conducted during the final data generation and analysis phase.

Figure 26: Plot showing the percentage of hydration change over time for a human study. The graph includes additional information from the participant's activity log overlaid on it. This visualization provides a clear representation of how hydration levels, adjusted for temperature, fluctuate over time and how they relate to the activities performed by the participants

Good data versus Bad data

The S11 graphs have played a crucial role in distinguishing between good and poor quality data. In Figure 27, an example of a study with unfavorable data is presented, exhibiting significant fluctuations in the S11 magnitude vs time graph. These fluctuations in s11 (the black line) can be attributed to a broken end of the coaxial cable. By visually representing such instances, the S11 graphs have proven helpful in identifying data anomalies and aiding in the overall assessment of data quality.

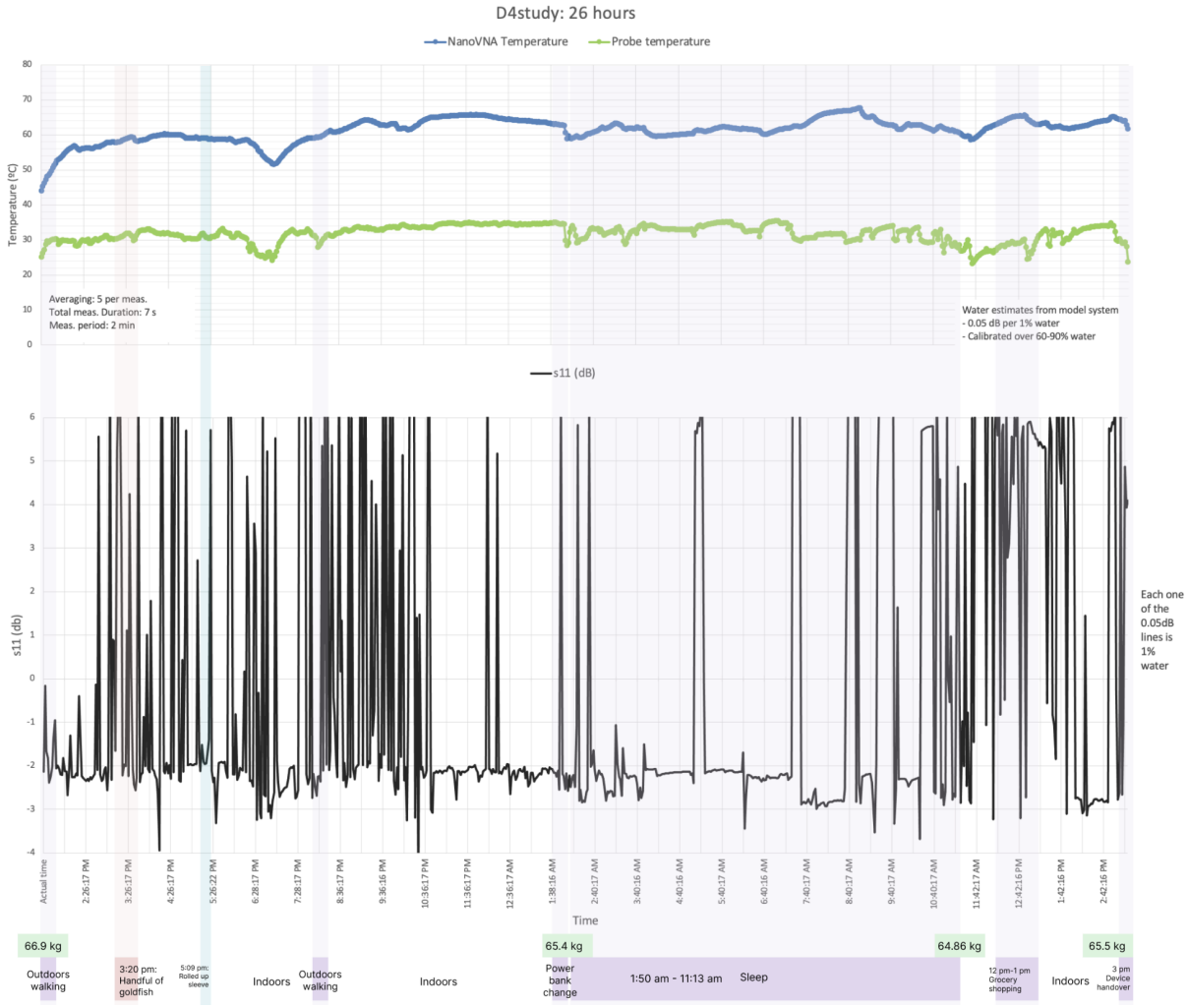


Figure 27: This graph represents a non-qualifying human study with bad data due to a lot of fluctuations in the S11 magnitude throughout the study.

Figure 28 on the other hand depicts a study with stable s11 magnitude data (black line). The data fluctuation in the beginning and the end of the study is the period when the probe was

not worm by the participant.

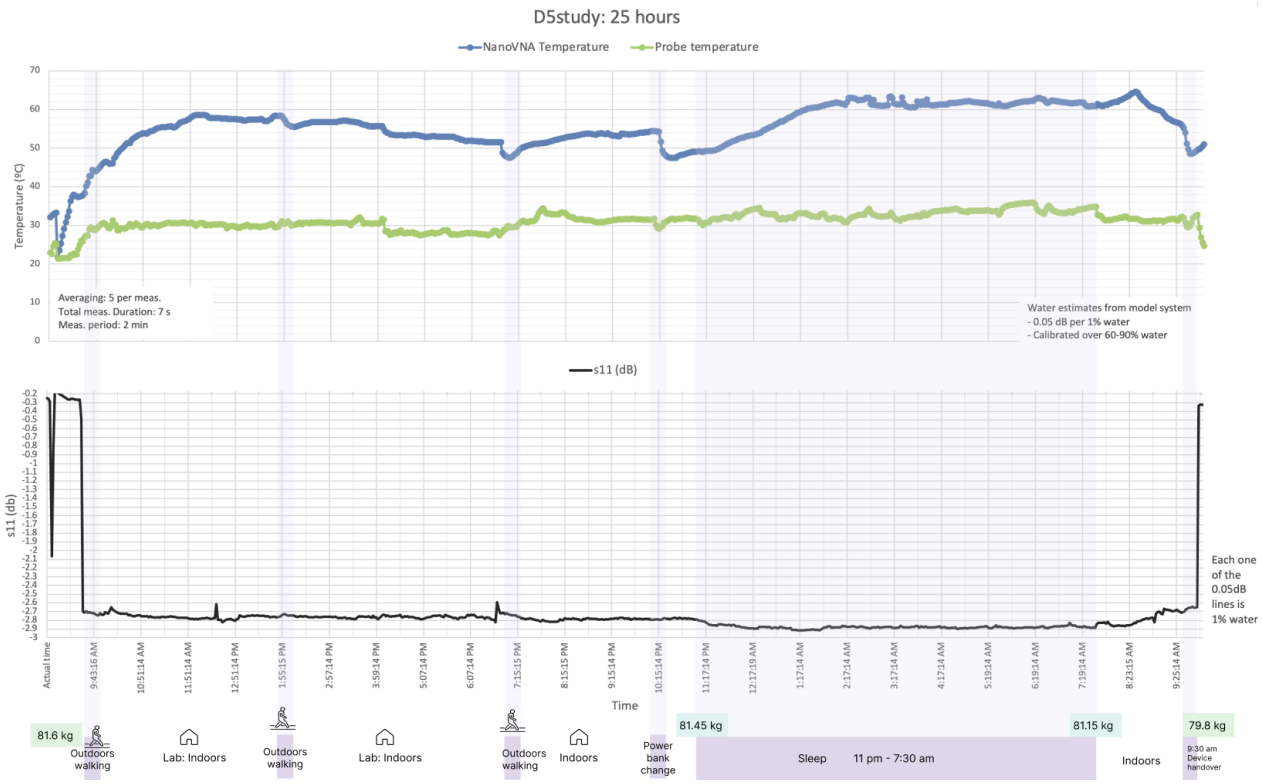


Figure 28: Plot of a qualifying human study, revealing consistent and reliable data. The graph visually represents the limited fluctuations observed in the s11 magnitude, indicating a stable pattern throughout the study. These results highlight the robustness and reliability of the measured s11 magnitude in this particular human study

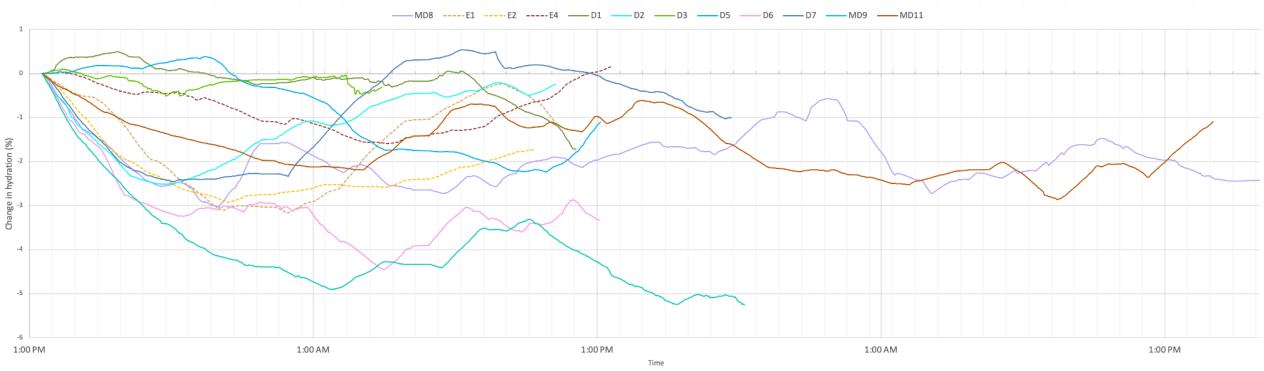


Figure 29: Plot of temperature-corrected hydration percentage change over time for all studies in two cohorts. Additional analysis is needed to understand the hydration changes in each study due to differences in start time, sleep times, and activities.

To comprehensively visualize the data from all 16 human studies conducted in both cohorts, Figure 29 was generated to depict the percentage change in hydration over time. The duration

of these studies varied from 20 hours to 53 hours, this graph allows us to visualize how hydration levels fluctuated across different study durations. However, it is important to note that conclusive findings are challenging to ascertain at this stage as the starting point in the day for the study was different across the studies. Further studies are required with a consistent protocol while ensuring the device operates optimally throughout the entire study period.

Chapter 8: Results & Recommendations

This chapter aims to provide a comprehensive overview of the data quality, trends, and insights obtained from the wearable setup throughout the studies. The current iteration of the wearable setup has demonstrated its capability to collect stable data, allowing for the possibility of conducting further human studies. However, due to the iterative nature of the studies and the limited duration of the thesis period, it is challenging to draw consistent and reliable conclusions from just the current collected data.

Recruitment results

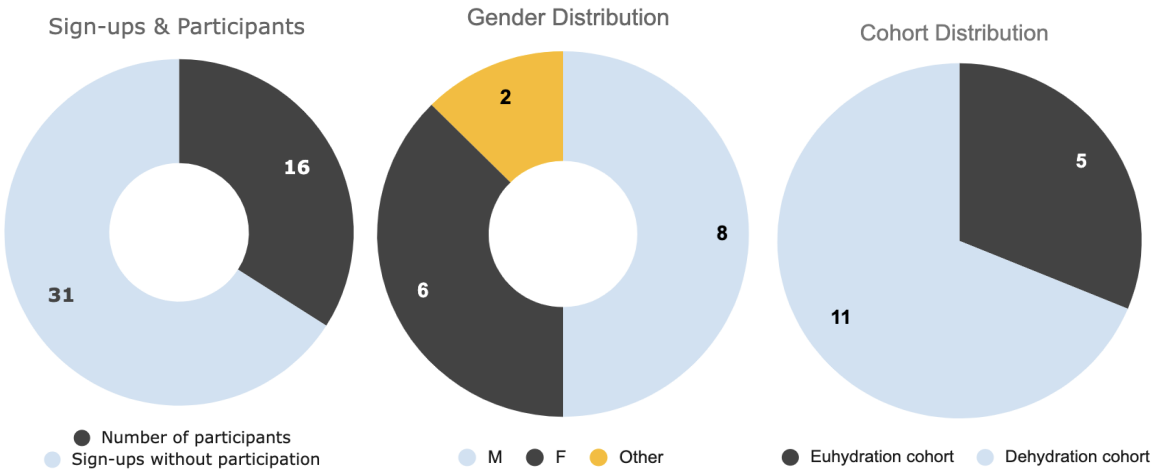


Figure 30: Graphs showing the participant numbers, gender distribution, and cohort distribution of the total participants recruited in the human studies

In response to the recruitment intake form, a total of 47 individuals completed the form, expressing their interest in participating in the study. Out of these respondents, 16 participants successfully participated in the human studies. The participants were divided into two cohorts: the Euhydration cohort, consisting of 5 participants, and the Dehydration cohort, consisting of 11 participants.
Regarding the gender distribution among the participants, there were 8 male participants, 6 female participants, and 2 participants who identified as another gender category.

Data Quality Review

To ensure data quality and reliability, a thorough data quality review was conducted, selecting studies where the wearable device functioned optimally and participants adhered

to the study protocol. The selected studies were then divided into segments based on participant activity, distinguishing between awake and sleeping periods to identify potential trends in hydration levels. From the extensive dataset gathered in both cohorts, the studies were carefully reviewed to determine qualifying data that could be subjected to further analysis, as presented in Table 3.

In Table 3, one of the qualifying parameters is if the equipment was working well. This parameter considered factors like if no cables were broken, if all the connections were secure throughout the study, if all the components stayed on throughout the device, if the probe and armband stayed on the same arm, or any dysfunction of the hardware components of the device. The details of each study's data stability can be found in Table 2 in Chapter 6.

Another crucial parameter is if the subject was adhering to the protocol covered in the earlier chapters which essentially means if the dehydration cohort maintained their fast for 24 hours and the Euhydration cohort was hydrated throughout the day and not dehydrating unintentionally.

Study Name	Cohort	Study Duration (hh:mm)	Weight change during Euhydration/ Dehydration period (kg)	Weight change while sleeping (kg)	Equipment was operating well or not	Did the subject conform to study or not
E1	Euhydration	24:40	-0.5	-0.6	Yes	Euhydration - lack data about liquid intake
E2	Euhydration	23:30	-0.7	-1.25	For 20 hours	Euhydration - lack data about liquid intake
E3	Euhydration	24	-0.6	-2.6	Yes	Euhydration - lack data about liquid intake
E4	Euhydration	25	0.1	-0.5	Yes	Euhydration - lack data about liquid intake
D1	Dehydration	24	-1.4	-0.4	No	Yes
D2	Dehydration	19:40	-2.4	-1.2	For 21 hours	Yes
D3	Dehydration	25	-1.1	-1.2	No	No
D4	Dehydration	25:30	-1.4	-0.5	No	Yes
D5	Dehydration	24:30	-1.8	-0.3	Yes	Yes
D6	Dehydration	24:30	-2.3	-1	Yes	No
MD7	Dehydration	31:30	not known (more than 24 hours)	-0.5	No	Yes
MD8	Dehydration	53	not known (more than 24 hours)	-0.7	Yes	Ended fast at 21 hour mark
MD9	Dehydration	28	not known (more than 24 hours)	-0.4	Yes	Yes
MD10	Dehydration	73	0.9		No	Yes

MD11	Dehydration	48	not known (more than 24 hours)	-0.5	Yes	Yes

Table 3: Human study data Qualifying analysis

Although the data presented in this study is not final and more stable data needs to be collected, a potential approach to analyze the data is to compare the results from qualifying studies. Qualifying studies refer to those in which the device and its components were functioning properly, and participants adhered to the study protocol. The qualifying studies are denoted by bold study numbers in the first row of Table 4, and the corresponding study columns are shaded.

Data analysis of the qualifying studies in the Dehydration Cohort

Within the conducted Dehydration studies, a subset of five studies (D2, D5, MD8, MD9, and MD11) emerged as qualifying for further analysis. In Figure 31, the dehydration segment of the MD8, MD9, and MD11 studies (which lasted more than 24 hours) has been included. These studies exhibited consistent device functionality and adherence to the study protocol, warranting their inclusion in the subsequent examination. In order to gain insights from these qualifying dehydration studies where the participants were fasting with the liquid intake limited to 8 ounces, Figure 31 showcases the temperature-corrected percentage change in hydration plotted over time.

Figure 31 provides observations regarding the starting and ending hydration levels within the qualifying dehydration studies. By the end of the dehydration study period, D2 exhibited a decrease in hydration of 0.2%, D5 experienced a decrease of 1%, MD8 demonstrated an increase in hydration of 1.2%, MD9 indicated a decrease of 4% in hydration levels, and MD11 indicated a decrease of 1% in hydration levels. In terms of weight change, D2 showed a decrease of 2.40 kg, while D5 experienced a decrease of 1.8 kg. Unfortunately, the body weight loss for MD8, MD9, and MD11 could not be determined due to the participant's inability to measure their weight at the conclusion of the fasting period in the longer study duration.

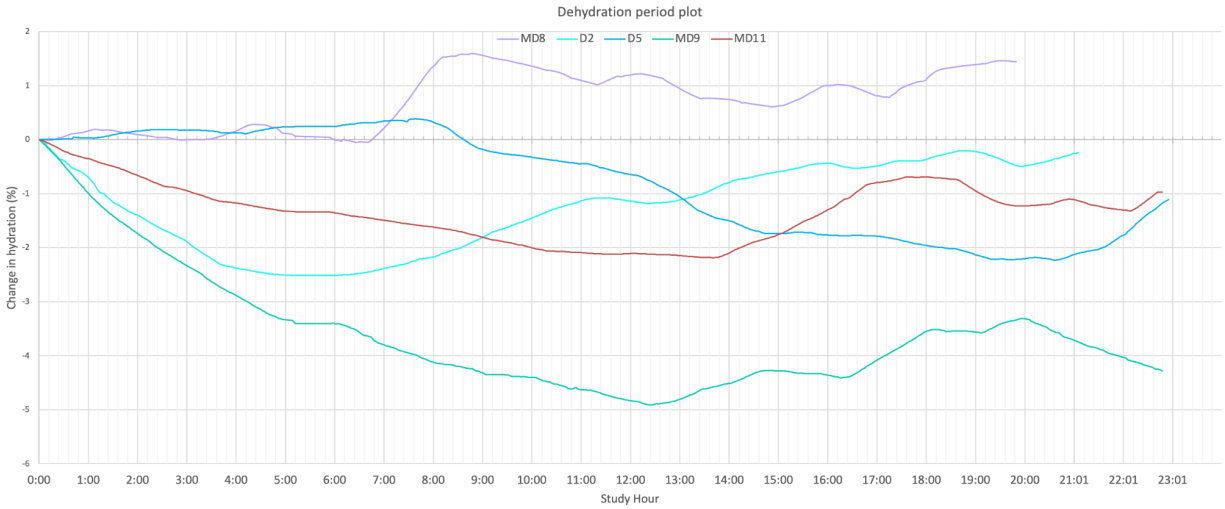


Figure 31: Plot of temperature-corrected percentage change in hydration over time for qualifying dehydration studies. Includes 24-hour studies D2 and D5, as well as the 24-hour dehydration periods from longer studies MD8, MD9, and MD11. The plot demonstrates variations in hydration levels, which will be examined further in subsequent plots based on participant activities

However, given the disparity in the start times of these dehydration studies (D2: 11:20 am, D5: 9:24 am, MD8: 3 pm, MD9: 1:20 pm), a direct comparison of the entire duration of these studies without accounting for different time periods, such as sleep and wake cycles, may yield limited interpretability. To address this challenge and facilitate a more nuanced analysis, Figures 32 and 33 provide subsets of the qualifying dehydration studies, dividing the 24-hour duration into distinct segments.

Figure 32 focuses on the period from the initiation of each study until bedtime, allowing for an examination of the hydration trends during awake hours. By isolating this specific timeframe, it becomes possible to explore the fluctuations and patterns in hydration levels throughout participants' active periods.

In contrast, Figure 33 delves into the duration encompassing the participants' sleep cycles. This subset concentrates solely on the hydration dynamics observed during the period of sleep, thereby offering insights into the nighttime variations and the impact of rest and lying down for a prolonged time on hydration levels.

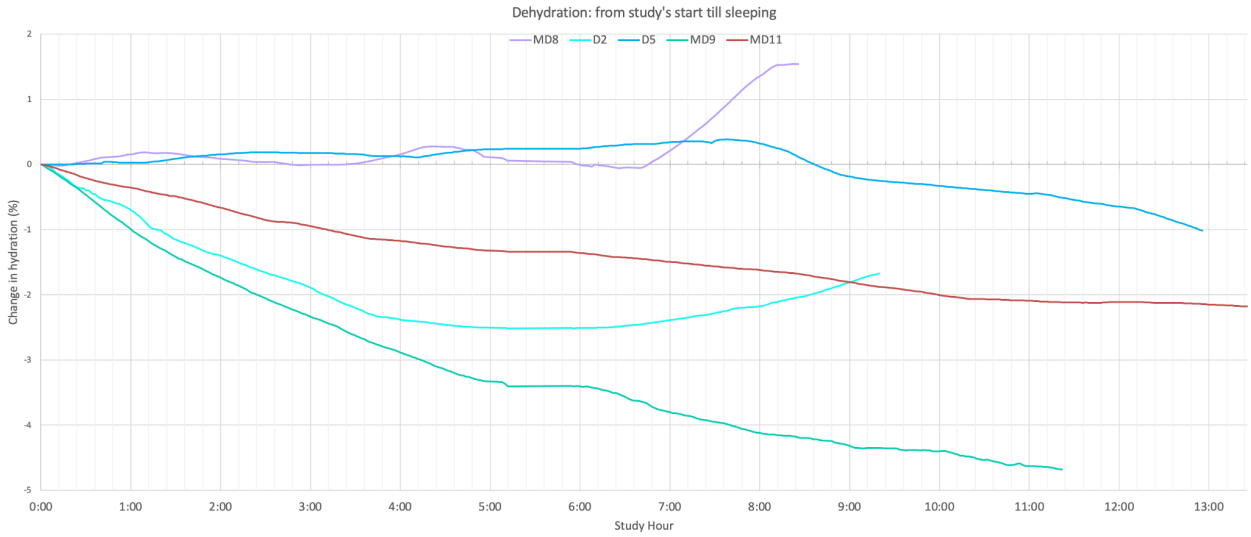


Figure 32: Plot of temperature-corrected percentage change in hydration over time, covering the period from the start of the study until bedtime for qualifying dehydration studies. In four out of five studies, a noticeable decrease in dehydration levels can be observed.

Figure 32 provides a visualization of the percentage change in hydration levels of the qualifying hydration studies in the period from starting the study until bedtime. By the end of the day before sleeping, D2 exhibited a decrease in hydration of 1.7%, D5 experienced a decrease of 1%, MD8 demonstrated an increase in hydration of 1.5%, MD9 indicated a decrease of 4.7% in hydration levels, and MD11 indicated a decrease of 2.1% in hydration levels. Further, Figure 33 provides a visualization of the percentage change in hydration levels of the qualifying hydration studies in the period the participants were sleeping. Zero here for all the studies is the starting point of their sleep time at the level of hydration they were. By the morning when they weighed themselves after voiding urine, D2 exhibited an increase in hydration of 1.25%, D5 experienced an increase of 1%, MD8 demonstrated a decrease in hydration of 0.75%, MD9 indicated a decrease of 1% in hydration levels, and MD11 indicated an increase of 0.25% in hydration levels.

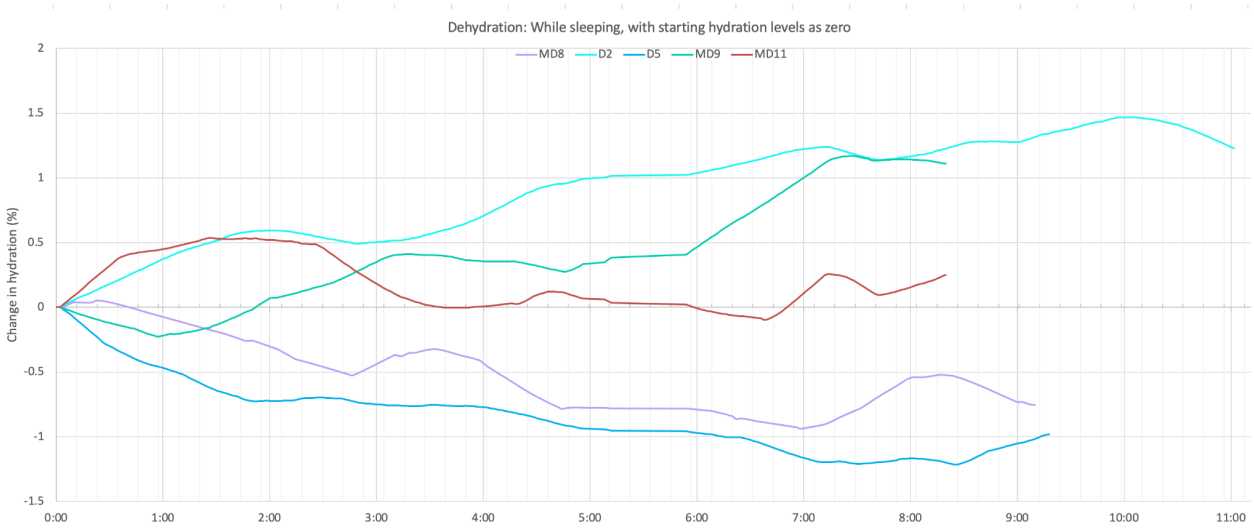


Figure 33: Plot of temperature-corrected percentage change in hydration over time during sleep for qualifying dehydration studies. The starting hydration point of each study at the sleep time is considered zero, based on their initial hydration level. Three studies exhibit an increase in hydration levels, while two studies display a decrease in hydration levels

During the study, participants were monitored for weight changes by weighing themselves before bedtime and in the morning after voiding urine while maintaining the fasting period. The analysis of nighttime weight changes revealed interesting findings. Specifically, in the D2 study, participants experienced a weight decrease of 1.2 kg, while in the D5 study, the weight decreased by 0.3 kg. Similarly, the MD8 study showed a weight decrease of 0.7 kg, the MD9 study exhibited a weight decrease of 0.4 kg, and the MD11 study exhibited a weight increase of 0.4 kg (the weight increase was noticed due to consumption of water in the night). This data has also shown in Table 4 in the form of the percentage weight loss and percentage change in hydration.

However, it is worth noting that there was a discrepancy between the observed weight loss and the corresponding change in hydration levels in D2 and D5. One possible explanation for this is that when a person changes their body position from upright to lying down, it can cause a redistribution of body water leading to an increase in the hydration level. To gain a deeper understanding of how the change in body position affects hydration levels, more focused studies will need to be conducted.

Study Name	Weight change (%)	Change in Hydration (%)
D2	-1.87%	1.25
D5	-0.37%	1

MD8	-1.18%	-0.75
MD9	-0.48%	-1
MD11	0.48%	0.25

Table 4: Comparison of Weight Change and Hydration Status during sleep of the qualifying dehydration studies. In three studies, an increase in hydration levels resulted in a discrepancy between overnight weight loss and percentage change in hydration. Further studies are needed to investigate this discrepancy and understand the correlation between percentage weight change and percentage change in hydration

Data Analysis of the Euhydration Studies

Within the conducted Euhydration studies, a subset of four studies (E1, E2, E4, and MD8 - the euhydration part of the study) were chosen for further analysis. These studies exhibited consistent device functionality and adherence to the study protocol, but it was not possible to track the amount of water each participant was consuming to stay hydrated. This has been realized to be important to track to make sure that the participant is not unintentionally dehydrating. In order to gain insights from these euhydration studies where the participants were not fasting and going about their day as they generally would, Figure 34 showcases the temperature-corrected percentage change in hydration level plotted over time.
Figure 34 provides observations regarding the changes in the hydration levels within the euhydration study duration. As can be seen, by the end of the study period, E1 exhibited a decrease in hydration of 1%, E2 experienced an increase of 0.9%, E4 demonstrated an increase in hydration of 0.2%, and MD8 indicated a decrease of 0.7% in hydration levels. In terms of weight change from the start till the end of the study, E1 showed a decrease of 0.5 kg, while E2 experienced a decrease of 0.7 kg, and E4 showed an increase of 0.1 kg. Unfortunately, the body weight change for MD9 could not be determined due to the participant's inability to measure their weight at the beginning of the euhydration section of their longer study period.

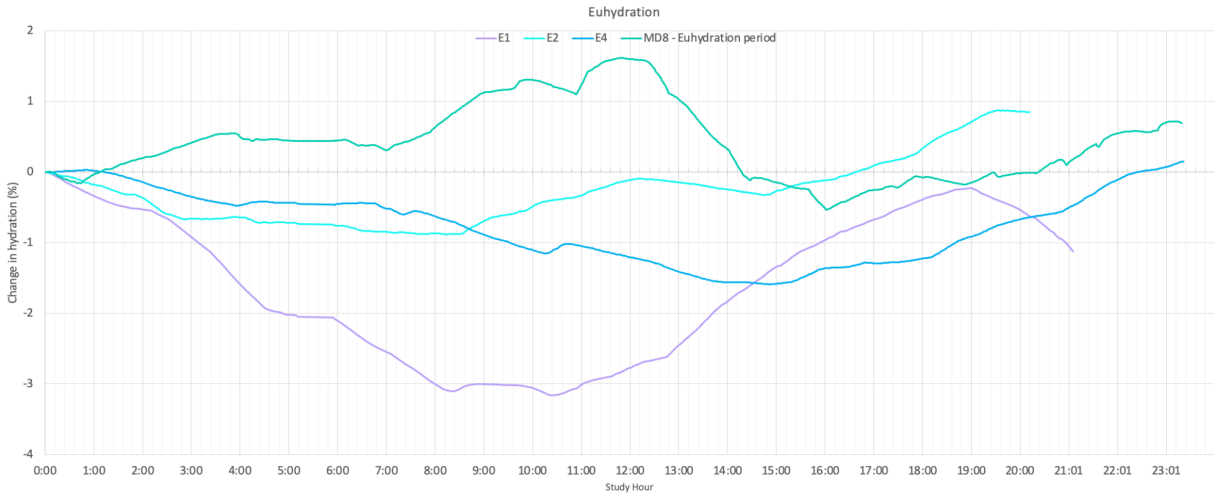


Figure 34: Plot of temperature-corrected percentage change in hydration over time for qualifying euhydration studies. Includes 24-hour studies E1, E2, and E4, as well as the 24-hour euhydration period from a longer study MD8. The plot demonstrates variations in hydration levels, which will be examined further in subsequent plots based on participant activities

Similar to the previous section, a direct comparison of the entire duration of these studies without accounting for different time periods, such as sleep and wake cycles, would not be helpful. To address this challenge and facilitate a more nuanced analysis, Figures 35 provides a subset of the euhydration studies, dividing the 24-hour duration into a distinct.

Figure 35 delves into the duration encompassing the participants' sleep cycle. This subset concentrates solely on the hydration level changes observed during the period of sleep, thereby offering insights into the nighttime variations and the impact of rest and lying down for a prolonged time on hydration levels. Zero here is the starting point of their sleep time and the level of hydration they were at while they went to bed. By the morning when they weighed themselves after voiding urine, E1 exhibited a decrease in hydration of 2.5%, E2 experienced an increase of 1.4%, E4 demonstrated an increase of 1.2%, and MD8’s euhydration period indicated an increase of 1.2% in hydration levels.

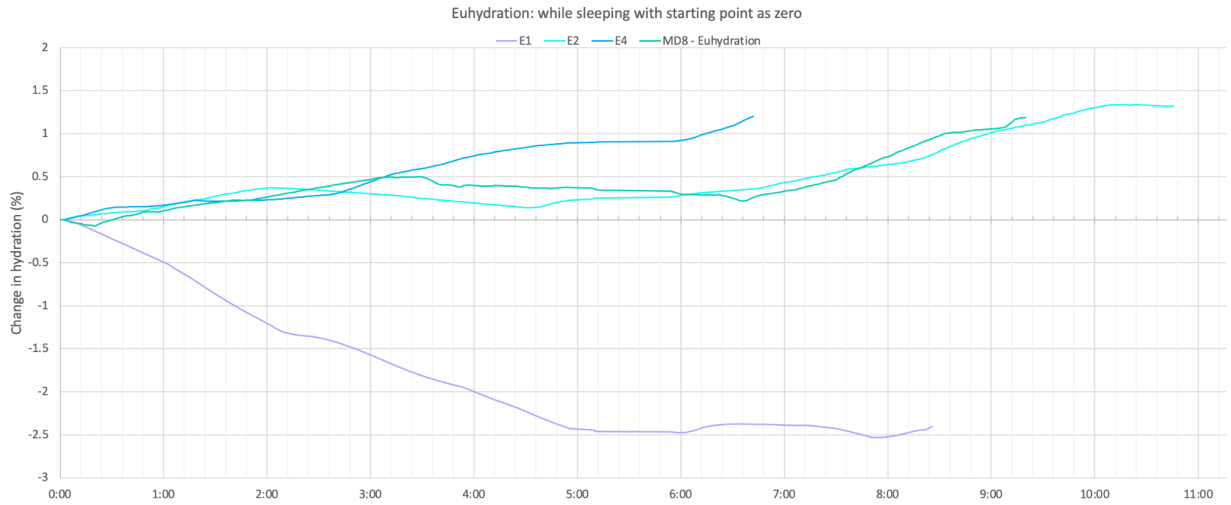


Figure 35: Plot of temperature-corrected percentage change in hydration over time during sleep for qualifying euhydration studies. The starting hydration point of each study at the sleep time is considered zero, based on their initial hydration level. Three studies exhibit an increase in hydration levels, while one study displays a decrease in hydration levels

During the study, participants were monitored for weight changes by weighing themselves before bedtime and in the morning after voiding urine before consuming anything. The analysis of nighttime weight changes shows that the participant in the E1 study experienced a weight decrease of 0.6 kg, while in the E2 study, the weight decreased by 0.7 kg. Similarly, the E4 study showed a weight decrease of 0.1 kg, and the MD8 study's euhydration period exhibited a weight decrease of 0.6 kg. This data has also shown in Table 5 in the form of the percentage weight loss and percentage change in hydration. Similar to the sleepy duration of the dehydration studies, there is a discrepancy between the observed weight loss and the corresponding change in hydration levels in E2, E4, and MD8's Euhydration period. The possible explanation could be the same that when a person changes their body position from upright to lying down, it can cause a redistribution of body water. To gain a deeper understanding of how the change in body position affects hydration levels, more focused studies will need to be conducted.

Study Name	Weight change (%)	Change in Hydration (%)
E1	-0.98%	-2.5
E2	-1.82%	1.4
E4	-1.02%	1.2
MD8 - Euhydration period	-1.01%	1.2

Table 5: Comparison of Weight Change and Hydration Status during sleep of the qualifying euhydration studies. Similar to the dehydration studies, an increase in hydration levels resulted in a discrepancy between overnight weight loss and percentage change in hydration in three studies. Further studies are needed to investigate this discrepancy and understand the correlation between percentage weight change and percentage change in hydration

Through these studies, the wearable setup has demonstrated its capability to collect stable data in certain studies; however, in order to draw definitive conclusions regarding the validation of the technology, it is imperative to gather more consistent and reliable data. Conducting additional studies is crucial to further explore and understand the trends observed in both the Euhydration and Dehydration cohorts.
A comprehensive and rigorous baseline setup, particularly through the euhydration study, holds great importance. This baseline study will serve as a reference point for comparing and contrasting the data collected during dehydration studies. By establishing a solid foundation with the euhydration study, we can effectively assess the variation in hydration levels with and without fasting and ascertain the validity and accuracy of the technology in measuring hydration levels.

Conclusion

Wearable Setup and Human Study Protocol

These studies have demonstrated the feasibility of the current wearable setup for conducting human studies outside of a laboratory environment, enabling the collection of stable and reliable data. The iterative process employed in refining the protocol design for a 72-hour study duration has resulted in the establishment of a standardized procedure for future data collection efforts. The combination of the wearable setup and the optimized protocol provides a methodology for further validation of the technology through additional studies.

Validating the technology outside a lab setup

Although the number of studies conducted thus far has been limited, notable percentage changes in hydration have been observed. However, it is important to validate and compare these findings with additional studies conducted under similar controlled conditions. By conducting more human studies, particularly in the Euhydration cohort, a comprehensive dataset and method to hydrate throughout the day can be achieved to establish a baseline for the percentage change in hydration. Further studies in the Dehydration cohort can provide valuable insights into the dynamics of hydration percentage changes during a 24-hour fasting period.

The current study has laid the groundwork for future investigations, highlighting the importance of conducting additional human studies to delve deeper into the understanding of hydration dynamics in both the Euhydration and Dehydration cohorts. This continuous exploration and data collection will contribute to the validation of the technology, paving the way for its development and use in the field of hydration assessment.

Limitations of the current prototype

Several limitations have been identified in the human studies and the wearable device used in this research, suggesting areas for improvement in future studies.

1. One limitation concerns the embodiment of the probe in an armband. It is unclear whether this placement has an impact on blood flow in the arm region or affects the water content on a tissue level around the armband. Even though the armband arrangement shows a decrease and increase in hydration levels, it could be worthwhile to explore a patch-based probe setup to compare the data collected.
2. Another limitation arises from the complexity of the device in terms of the multiple components and the process itself. This complexity of the hardware and the software procedure introduces the possibility of various failure modes, some already mentioned in this document and others unforeseen currently. Efforts could be made to enhance the reliability and robustness of the device by identifying and addressing potential failure points or by reducing or downsizing the device. The ongoing monitoring and refinement of the device design will be crucial to minimize sources of error and improve overall performance.
3. In terms of study design, there is room for improvement in the euhydration cohorts. These cohorts exhibited less control over participants' food and liquid intake, which can introduce variability in hydration levels. Implementing guidance or protocols to ensure consistent and adequate hydration throughout the study would enhance data quality and comparability within the euhydration cohort.

By addressing these limitations, future studies can refine the wearable device and optimize study protocols. This will lead to improved data quality, increased reliability, and a better understanding of hydration dynamics. Continued advancements in this area will contribute to the broader knowledge of wearable technology applications in hydration assessment and monitoring.

Recommendations

Several areas of improvement have been identified for the wearable setup used in the human studies and additional studies supporting the human study protocol:

1. Further studies are needed to understand the impact of body position (upright or lying down) on hydration levels in participants.
2. Introduction of pressure, accelerometer, and gyro sensors: The addition of an accelerometer and gyro sensor in the armband would enhance the device's capability to track the participant's movement during the study. This would provide valuable data on the participant's activities throughout the day, allowing for a more in-depth analysis of hydration level changes in relation to physical exertion and also information about the environment .
3. Development of a smaller-sized power bank: A smaller-sized power bank with extended battery life would be advantageous for prolonged studies. By reducing the size and weight of the power bank, the overall wearability and comfort of the device can be improved, enhancing participant compliance and reducing potential interference with daily activities.
4. Miniaturization or replacement of Raspberry Pi: To further reduce the size and weight of the device, exploring options to miniaturize the Raspberry Pi or replacing it with a more compact alternative could be beneficial. This would contribute to a sleeker and more lightweight design, making the device less obtrusive for participants and facilitating ease of use.
5. Downsizing the probe: Reducing the size of the probe used in the armband would contribute to making the overall device more compact. A smaller probe size would enhance the comfort and aesthetics of the armband, promoting participant compliance and reducing any potential discomfort associated with the current probe size.
6. Integration of the device into a smaller unit: To achieve a more streamlined and integrated design, efforts can be made to make the device smaller and inbuilt within the armband itself. This would eliminate the need for separate components and create a cohesive and discreet unit, enhancing user experience and overall device performance.

By addressing these areas of improvement, the wearable device can be optimized for future human studies. These advancements would enhance the device's functionality, user comfort, and data collection capabilities, ultimately leading to more reliable and efficient hydration assessment and monitoring.

Chapter 9: Future work: Hydration Monitoring Wearable Concept

In addition to the research studies conducted with the current device, a supplementary exploration focused on exploring the design and embodiment of a hydration monitoring wearable device. This form studies activity aimed to envision the physical appearance and practical aspects of a wearable device that can be comfortably worn on the body for extended periods of time on a daily basis.

The objective of this exploration was to understand the potential form factors and user experience considerations for a hydration monitoring device. By visualizing and prototyping different embodiments, we sought to gather insights into the feasibility, functionality, and user acceptability of such a device.

While the form studies activity provided valuable insights, further research and refinement are required to translate these concepts into a fully functional and market-ready device. Nonetheless, this exploration serves as a crucial step towards realizing the vision of a wearable device that can effectively monitor hydration levels over extended periods, contributing to improved health and well-being.

Possible product embodiments

During the form studies activity, potential designs for the hydration monitoring wearable were explored through early sketches (Figures 36, 37, and 38). These sketches presented concepts such as a strap-based wearable, arm patch, and ring-like wearable. To determine the most suitable design, a PUGH chart was utilized as a decision matrix. This allowed for a systematic evaluation of the three concepts, considering factors like functionality, comfort, and user experience.

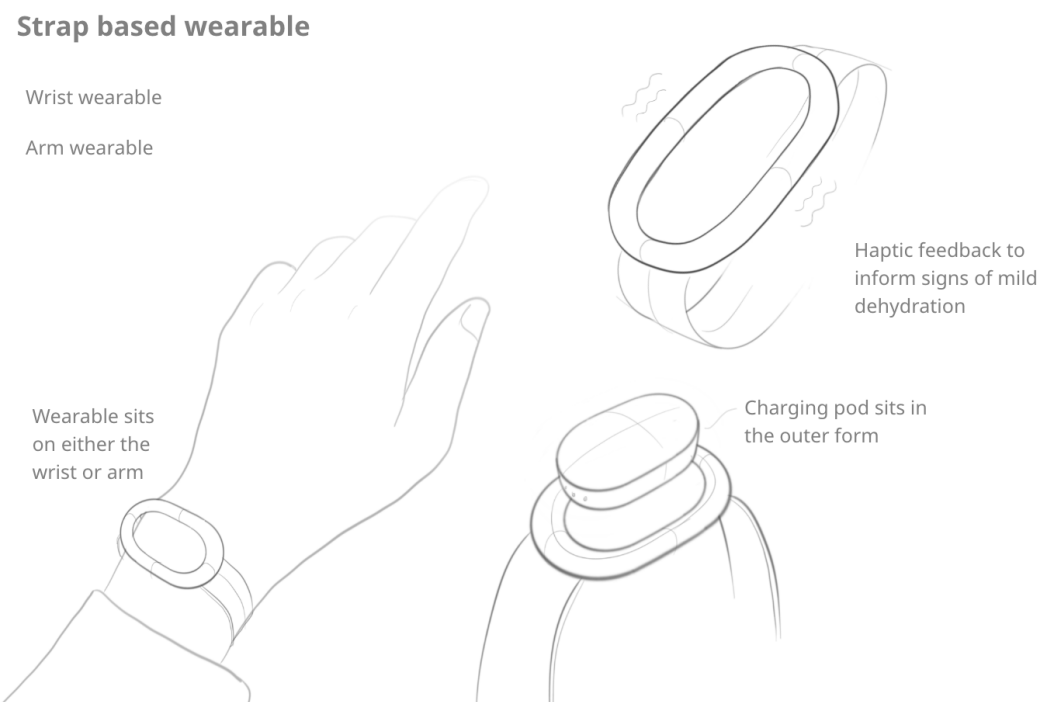


Figure 36: Concept sketch of a strap-based wearable

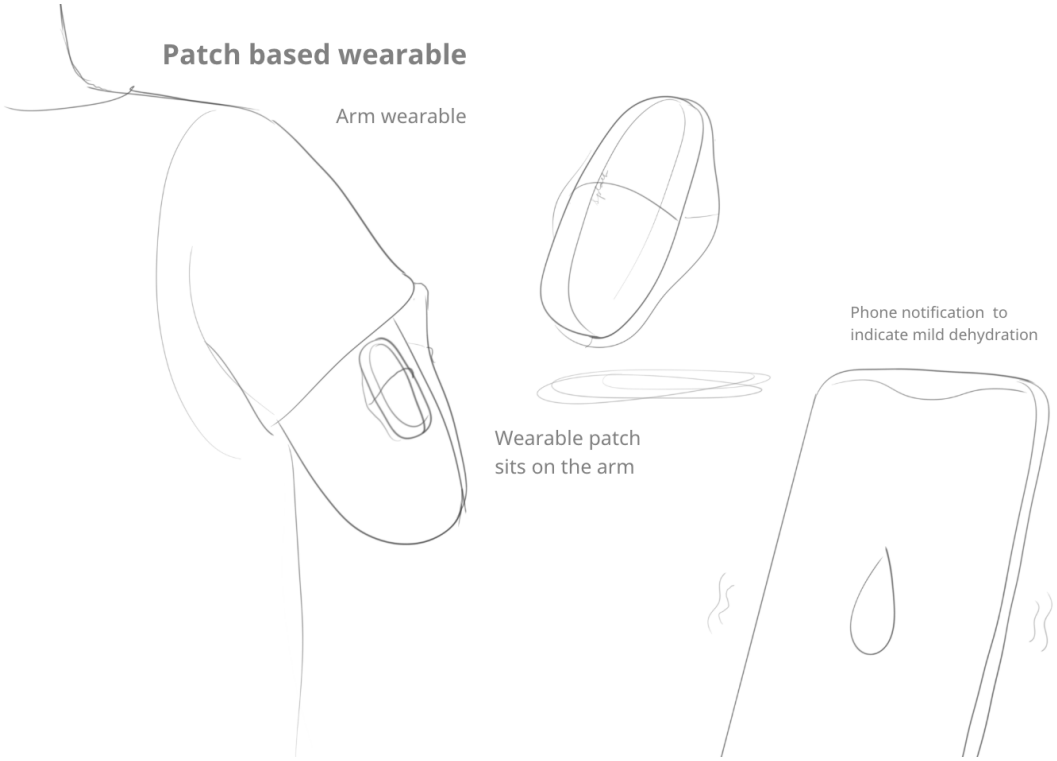


Figure 37: Concept sketch of a patch-based wearable

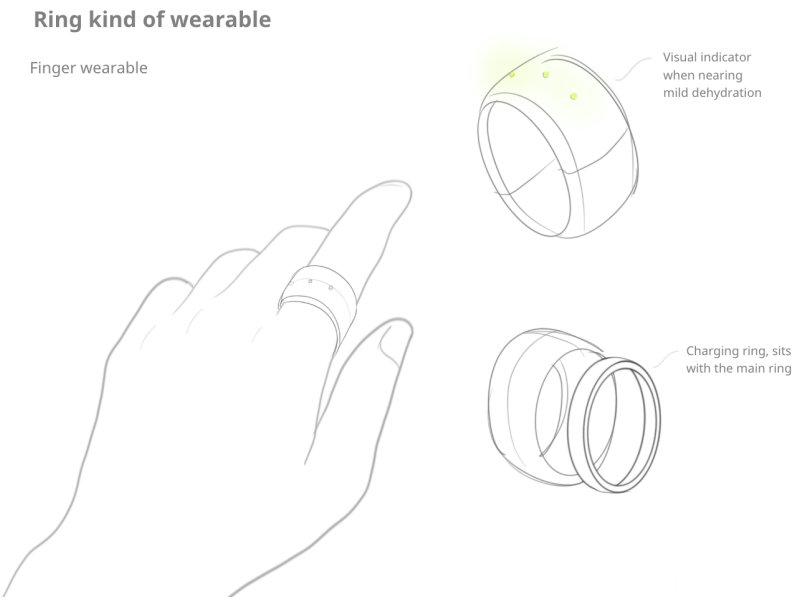


Figure 38: Concept sketch of a ring-like wearable

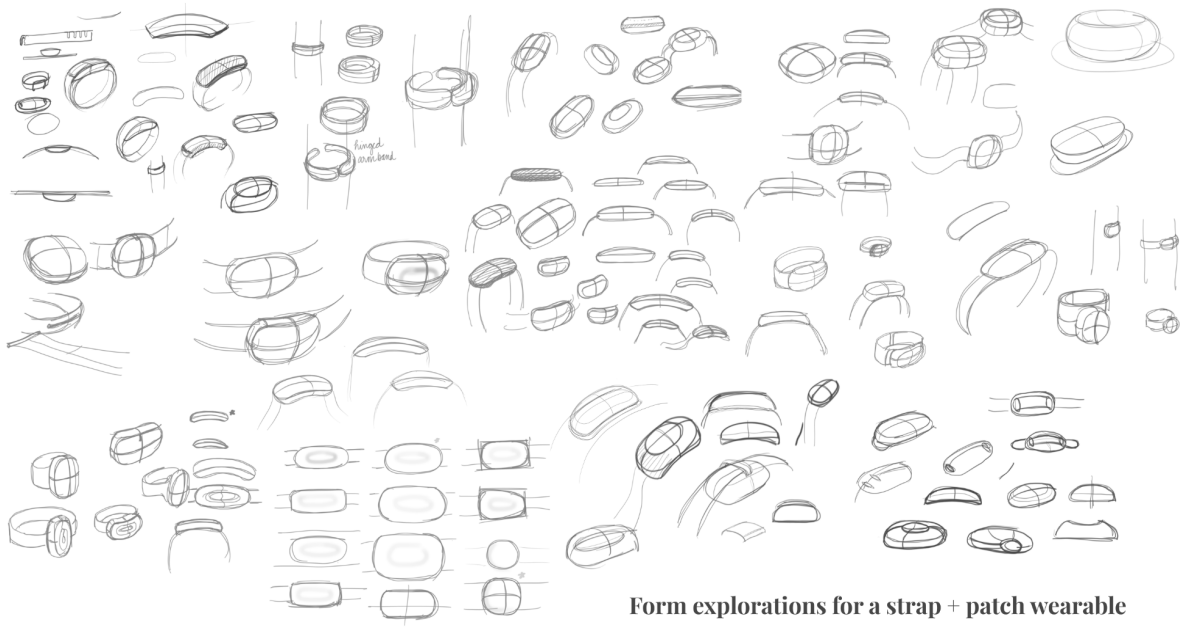
Pugh chart for the features vs different embodiments it can exist in (scale of 5)

	Wrist Band	Armband	Patch based product	Ring
Always be in contact with skin - no hair	1	4	4	3
Located where hydration can be measured	0	4	4	Not sure
Battery life to last a while 2-3 days for constant readings	3	4	4	2
Electronics packaging feasibility	4	4	3	0
Ease of putting on and off	4	3	3	5
User comfort: Long wear time	5	5	4	5
Stability of the probe at the location	4	4	5	3
Total	21	**28**	**27**	18

Table 6: Pugh chart to compare different embodiments

After careful consideration of the decision matrix based on the PUGH chart in table 6, two concepts emerged as more viable options for further development: the armband and the patch-based wearable. These concepts aligned with several important criteria, including the requirement for the wearable to always be in contact with the skin without interference from

hair, the ability to locate the device in an area suitable for accurate hydration measurement, and a battery life that allows for continuous readings over 2-3 days.
Additionally, the feasibility of electronics packaging, ease of putting on and taking off, user comfort during long wear times, and the stability of the probe at the selected location were also taken into account. The armband and patch-based wearables demonstrated promising potential in meeting these criteria, making them favorable options for further exploration and refinement in the development process.



Form explorations for a strap + patch wearable

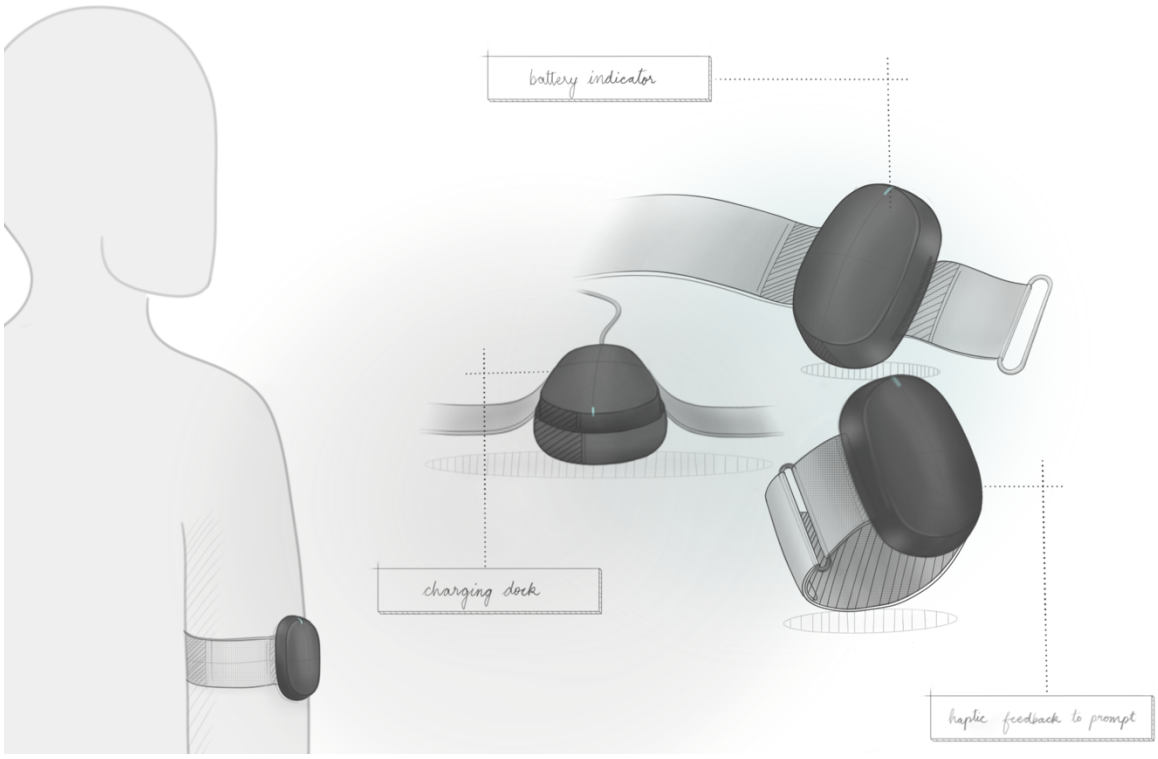


Figure 39: Form iterations brainstorming and concept

Figure 40: Visual language mood board

Adhesive patch and strap wearable concept

After consideration of all the sketches (figure 39) and mood boards (figure 40), the final concept (Figure 41) that emerged was a subtle-looking pod design. This innovative design offers flexibility for the user, as the pod can be easily snapped into either a strap or a patch as shown in figure 42, depending on their personal preference and comfort. The aim of this concept is to provide a versatile and adaptable wearable solution that seamlessly integrates into the user's daily routine. By offering multiple attachment options, the design ensures a comfortable fit while maintaining the essential functionality of the hydration monitoring device.

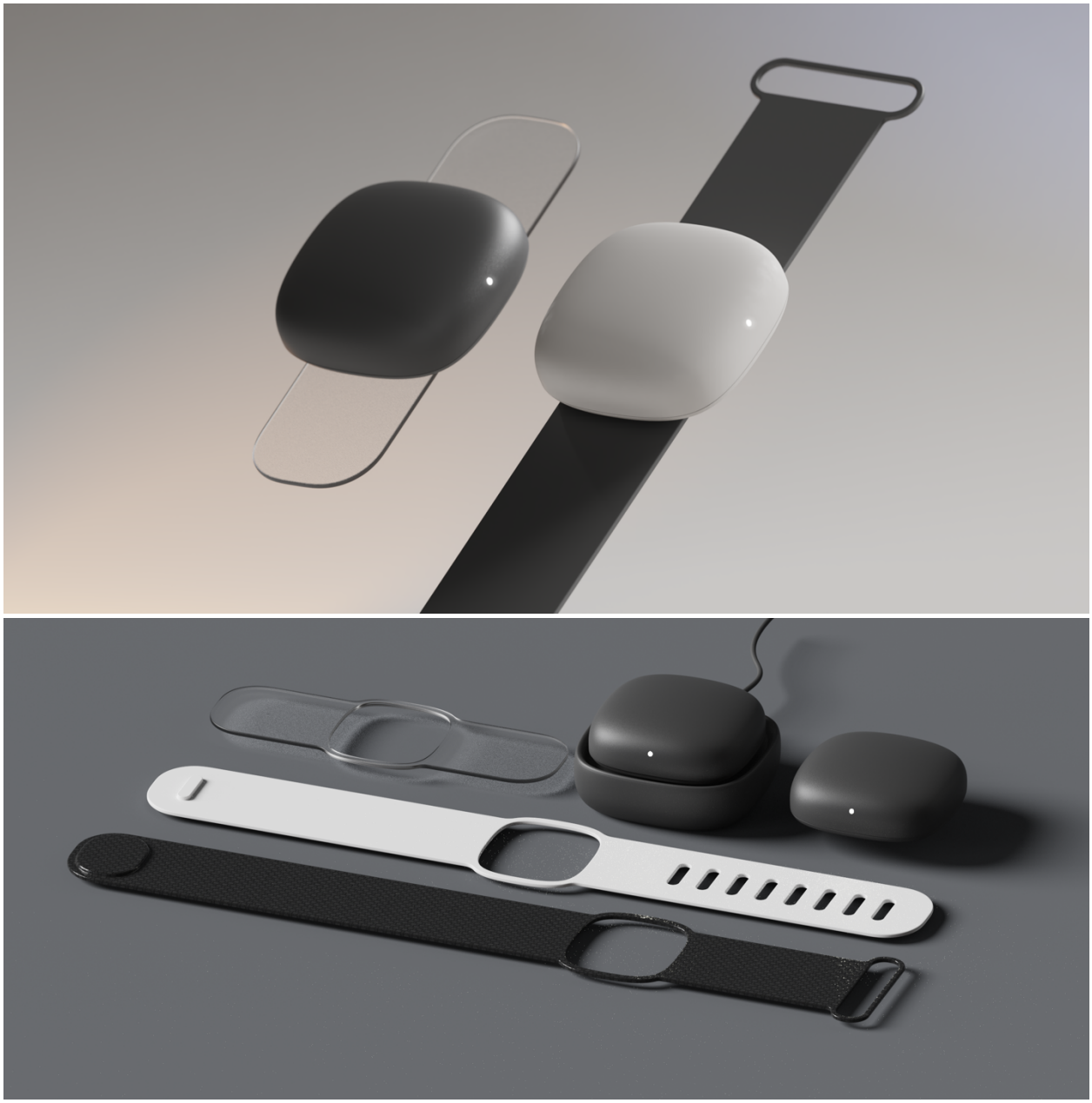


Figure 41: Final look at the wearable design concept

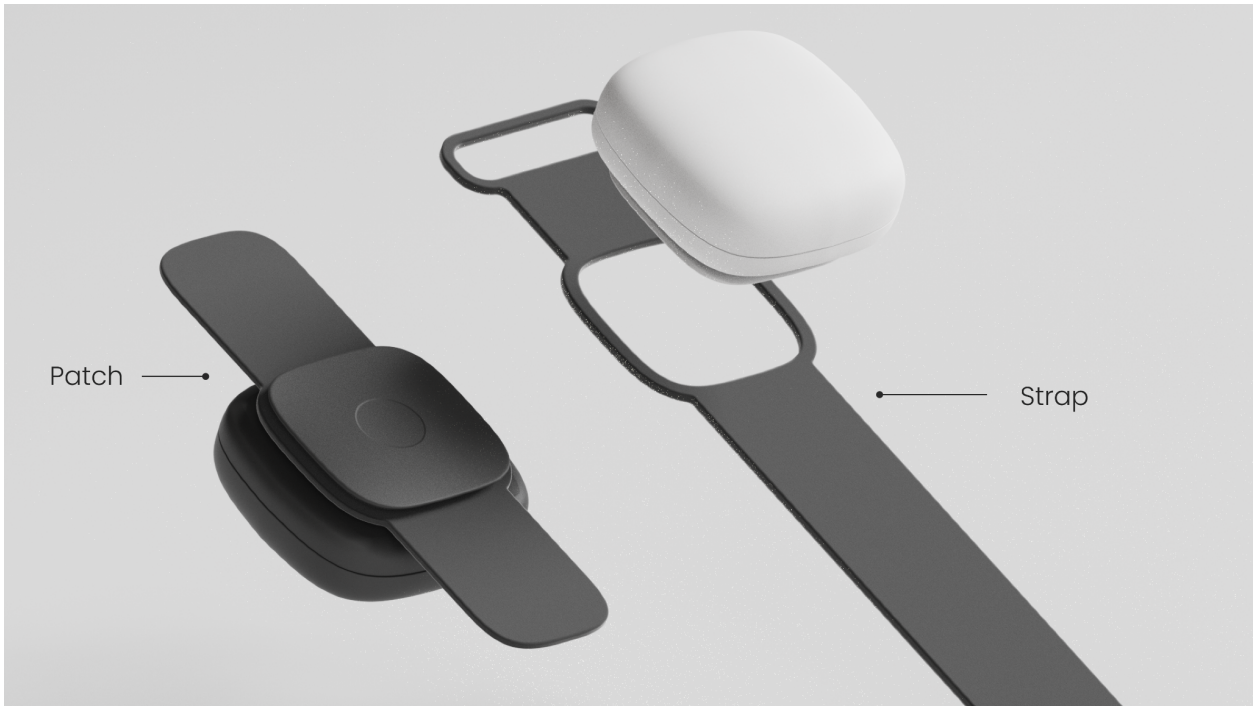


Figure 42: Patch and strap options for the pod to sit in

Figure 43: Charging dock for the pod

Figure 44: Different straps and finishes for the wearable

“
The closer an object gets to the human body, the easier it will be to adapt to if it has a softer, gentler form.
”

Naoto Fukasawa

Appendix

Data Visualization Iterations

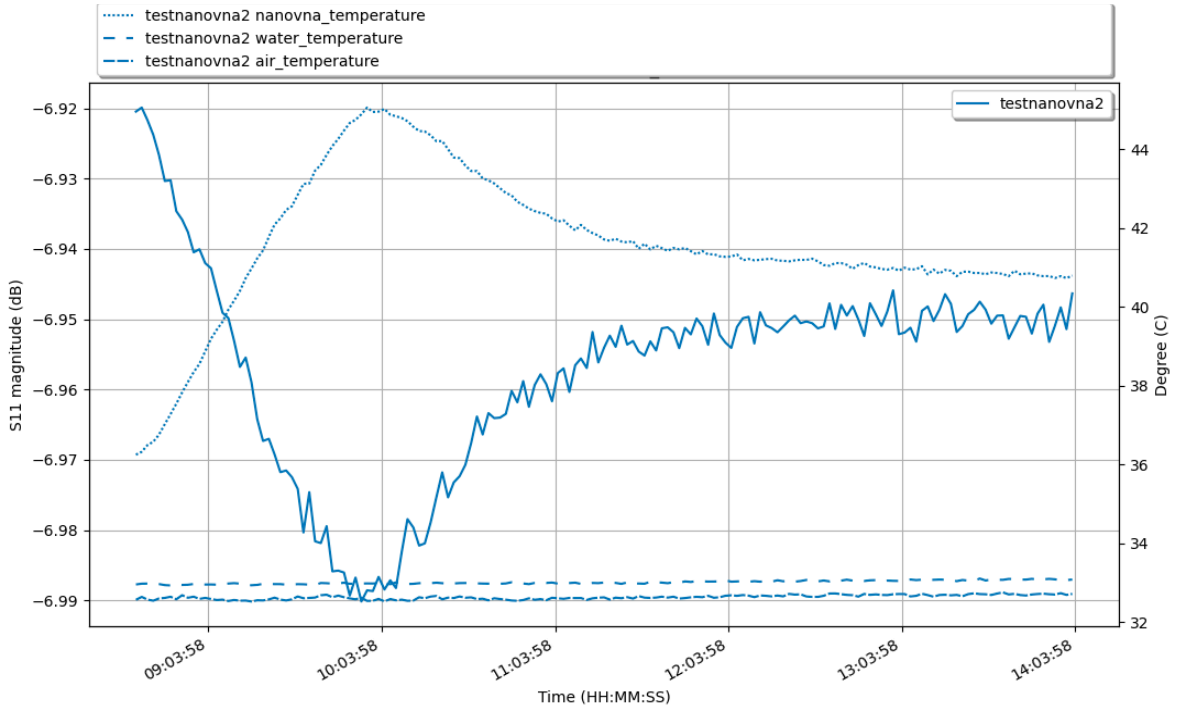
1. The first iteration shown in Figure 45 is the plot that can be generated from the Python code directly. One of the limitations of this plot was that the only differentiating factor between the S11 Magnitude and the temperatures was the line type which made it difficult to read.
2. 

Figure 45: Python plot with data differentiated through line types

3. Adding color in the Python code-generated plot to differentiate the S11 magnitude from the temperature readings as shown in Figure 46.

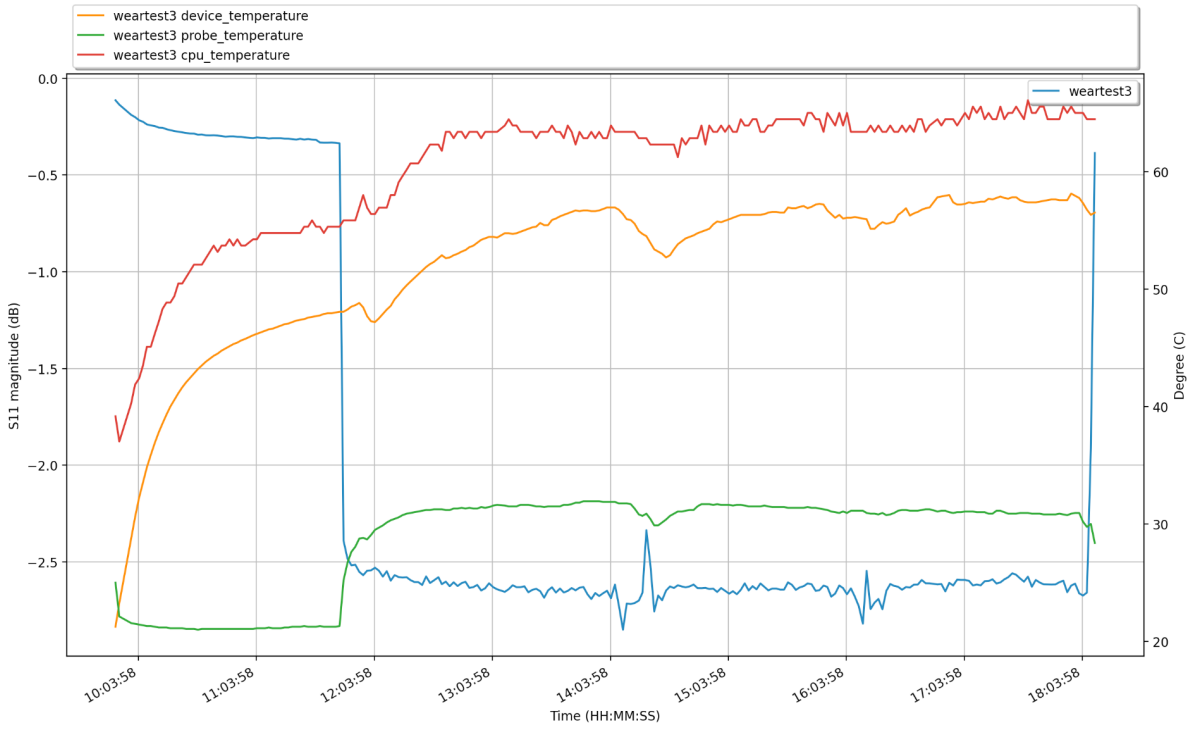


Figure 46: Python plot with data differentiated through colors

4. Figure 47 shows a plot made in Excel to provide more control and zoom into specific parts of the study. The plot has a primary vertical axis and a secondary vertical axis for assigned for the S11 magnitude and temperature respectively

Figure 47: Excel plot zoomed into the part of the plot where the device is on body

5. Figure 48 shows an Excel plot divided into two parts, one for the temperature readings and one for the s11 magnitude. This cleaned up the plot and reduced some confusion

while reading as the previous graphs had the primary and secondary vertical axis representing S11 magnitude and the temperature respectively.

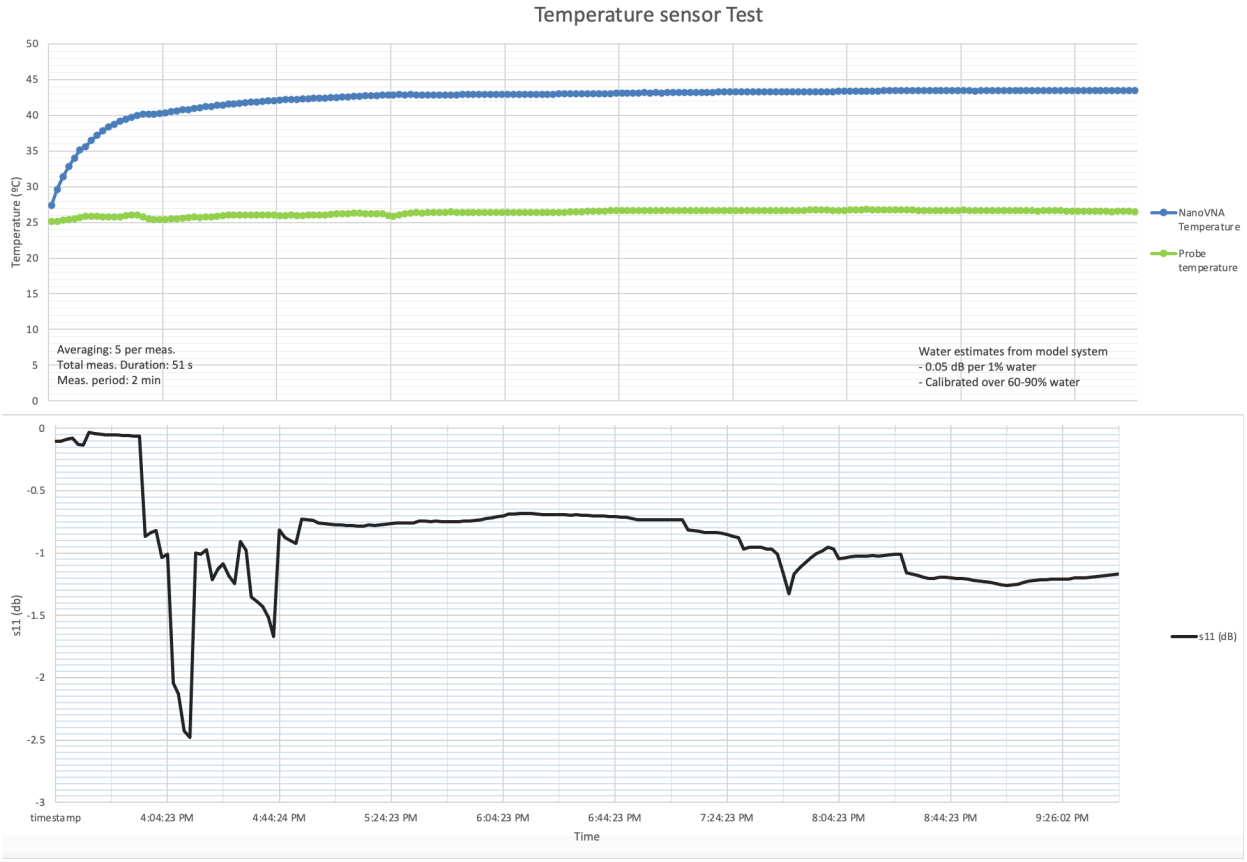


Figure 48: Separated temperature sensor and S11 magnitude graphs

6. Figure 49 shows the plot of the S11 magnitude and temperature vs time with activities the participant was conducting throughout the study duration to better analyze fluctuations and changes in data. These activities have been mapped on to the excel graphs through the Figma tool. Any fluctuations or irregular data has been easy to correlate to the activities being performed during that time period through this approach. This graph has been one of the final outputs of the data collection and analysis of all the human studies.

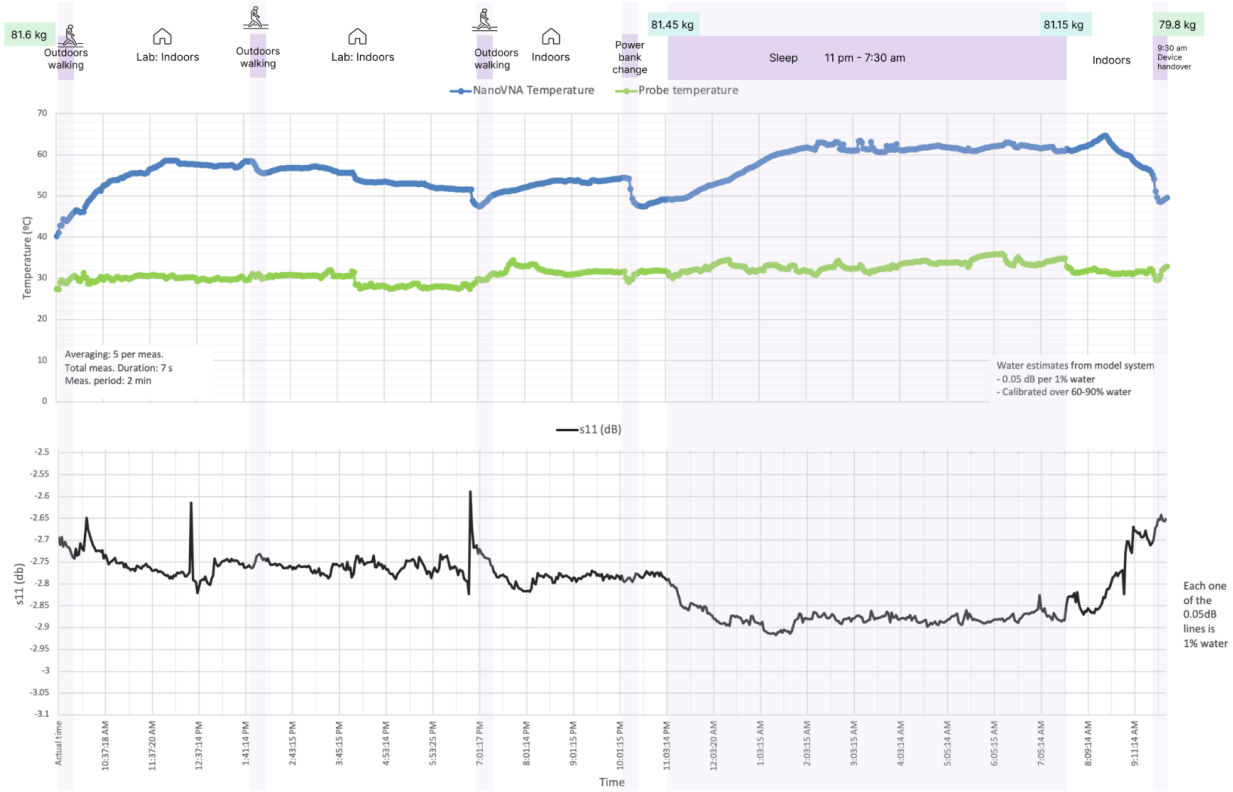


Figure 49: Plot showing the S11 magnitude and temperature changes over time in a human study. The graph also includes the participant's activity log details overlaid on it. It provides a representative visualization that showcases the fluctuations in the S11 magnitude.

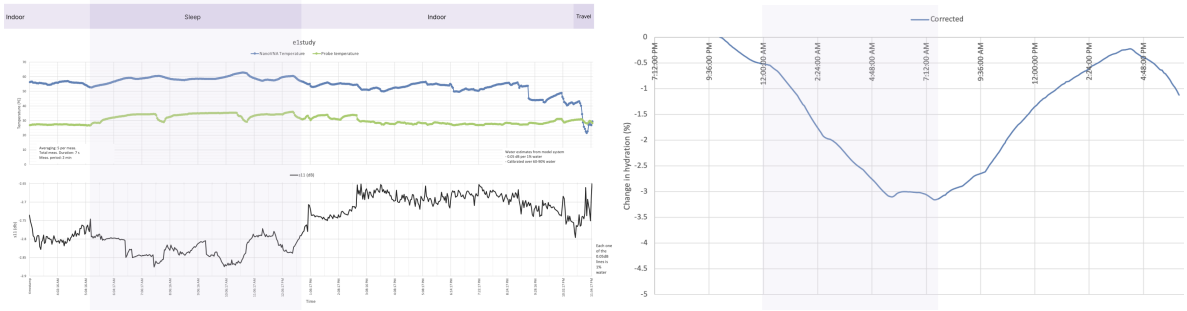
7. Figure 50 shows the change in hydration plot with temperature corrected values: A plot for the percentage change in hydration is made by correcting for the temperature change. The participant's activities are also overlayed in this graph. This kind of plot has also been generated for all the studies conducted as a part of the final data generation and analysis

Figure 50: Temperature corrected graph with activities aligned and overlayed

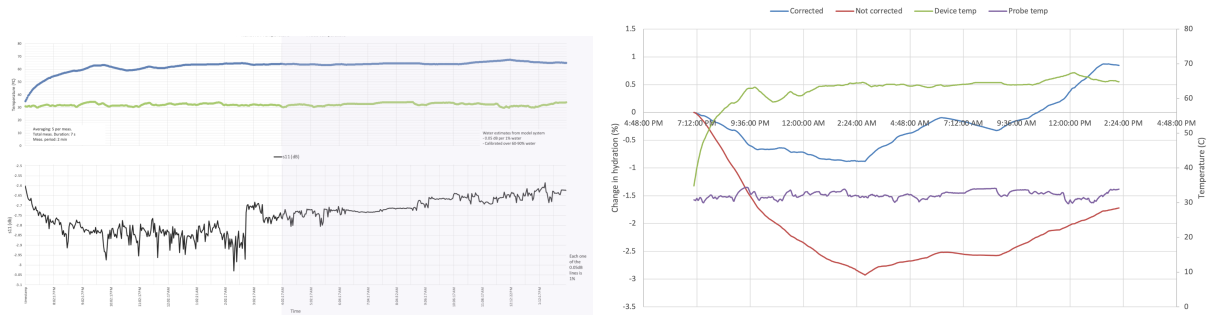
Human study data visualization

The S11 magnitude vs time plot and the Percentage change in Hydration vs time plot for each human study was mapped to better understand the results, any iterations, and to inform the next steps that would need to be taken.

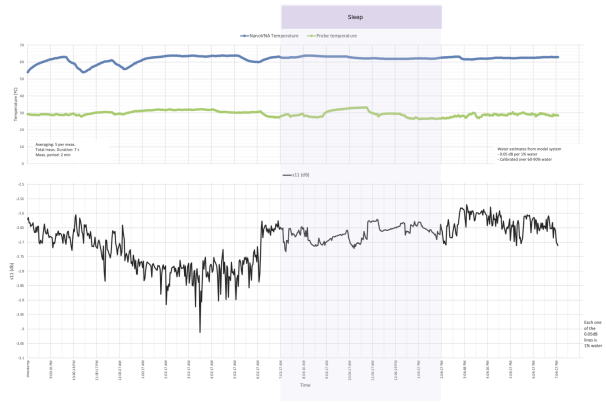
E1: Euhydration 1



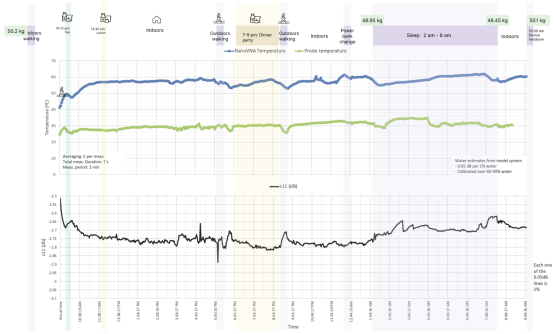
E2: Euhydration 2

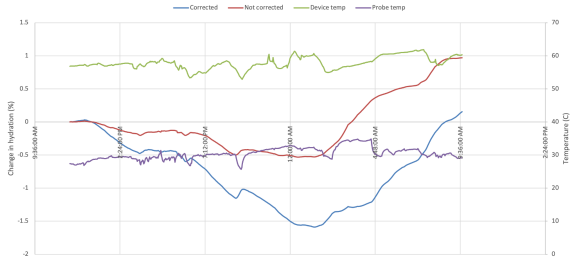


E3: Euhydration 3

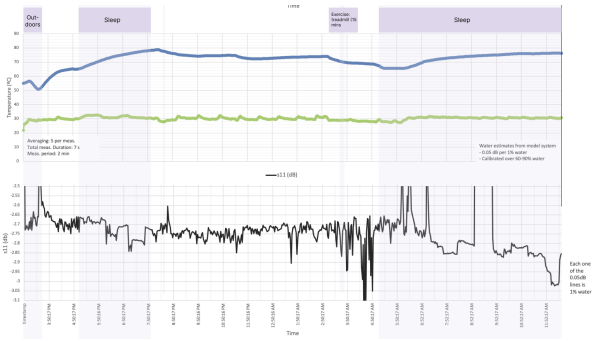


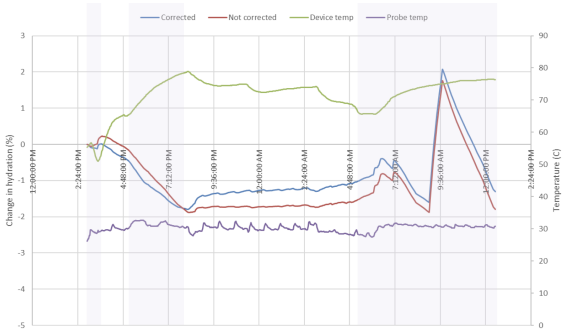
E4: Euhydration 4



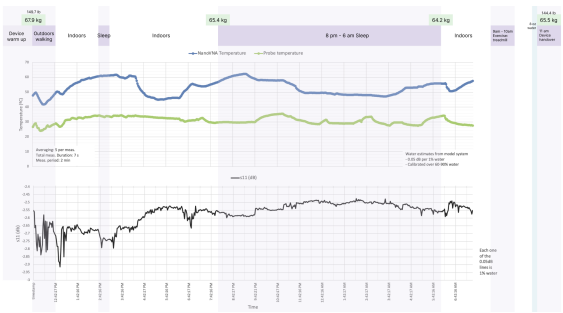


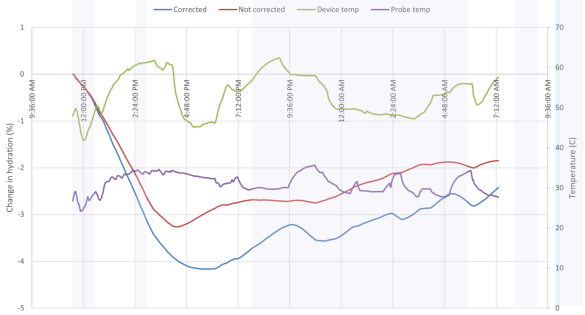
D1: Dehydration 1



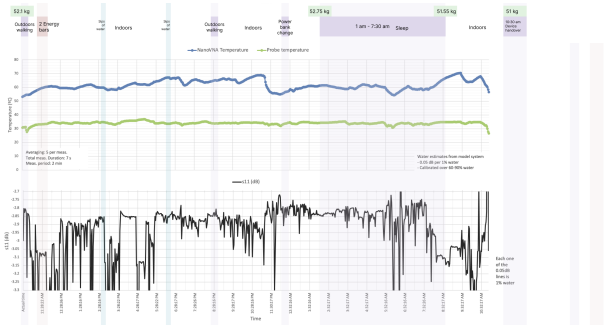


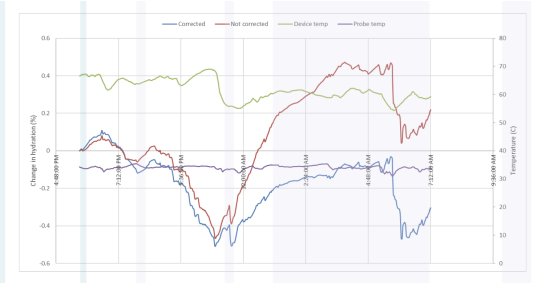
D2: Dehydration 2



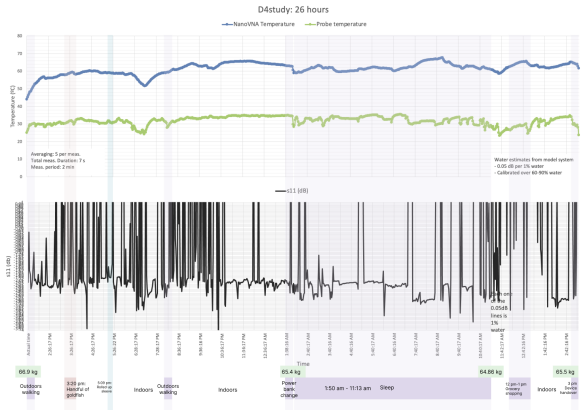


D3: Dehydration 3

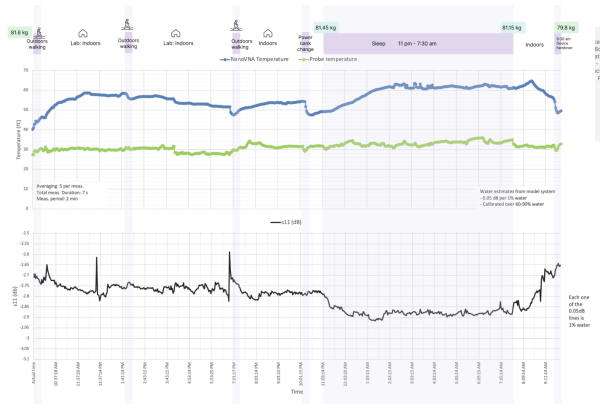




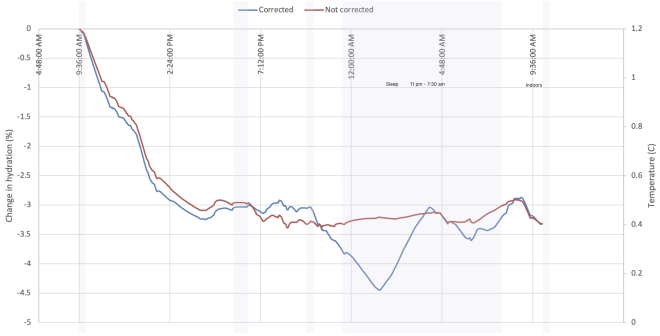
D4: Dehydration 1, S11 Magnitude fluctuations upto +6 due to a broken wire



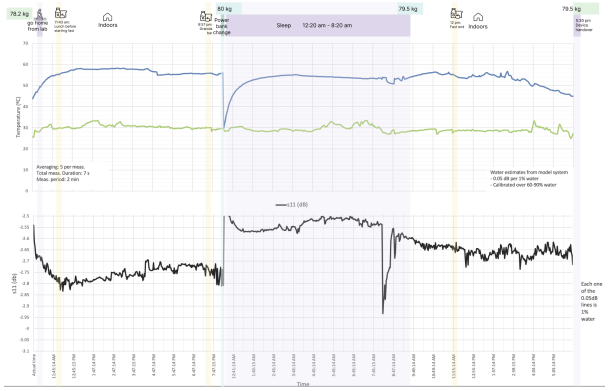
D5: Dehydration 5

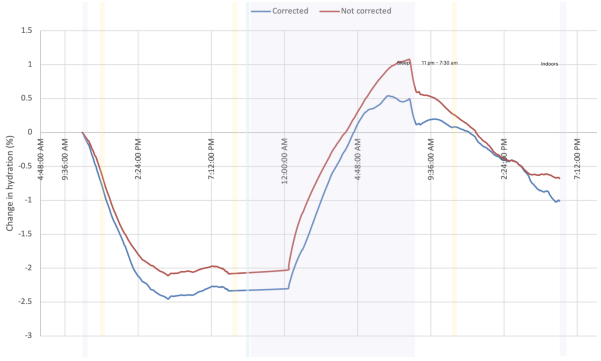


D6: Dehydration 6



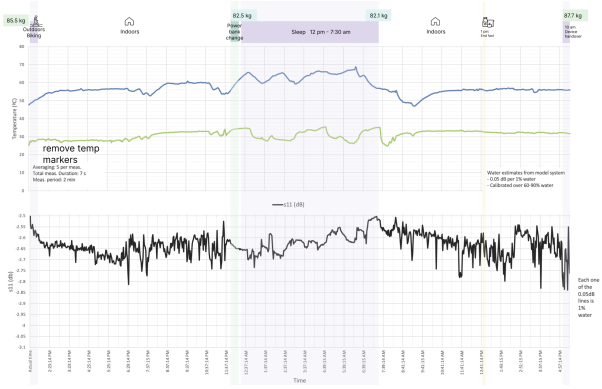
D7: Dehydration 7

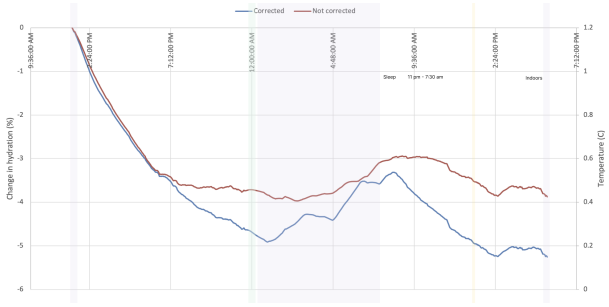




D8: Dehydration 8

D9: Dehydration 9





Citations

"20 Examples Of IoT Wearables Technology Disrupting Healthcare – Avenga," December 9, 2020. https://www.avenga.com/magazine/wearables-iot-healthcare/.

Ahmad, Ashfaq, Tareq Rasul, Anish Yousaf, and Umer Zaman. "Understanding Factors Influencing Elderly Diabetic Patients' Continuance Intention to Use Digital Health Wearables: Extending the Technology Acceptance Model (TAM)." *Journal of Open Innovation: Technology, Market, and Complexity* 6, no. 3 (September 2020): 81. https://doi.org/10.3390/joitmc6030081.

Baker, Lindsay B., Melissa S. Seib, Kelly A. Barnes, Shyretha D. Brown, Michelle A. King, Peter John D. De Chavez, Shankang Qu, et al. "Skin-Interfaced Microfluidic System with Machine Learning-Enabled Image Processing of Sweat Biomarkers in Remote Settings." *Advanced Materials Technologies* 7, no. 11 (November 2022): 2200249. https://doi.org/10.1002/admt.202200249.

"Basics of Measuring the Dielectric Properties of Materials," n.d.

Benton, David, Kimberly T Jenkins, Heather T Watkins, and Hayley A Young. "Minor Degree of Hypohydration Adversely Influences Cognition: A Mediator Analysis." *The American Journal of Clinical Nutrition* 104, no. 3 (September 2016): 603–12. https://doi.org/10.3945/ajcn.116.132605.

Benton, David, and Hayley A. Young. "Do Small Differences in Hydration Status Affect Mood and Mental Performance?" *Nutrition Reviews* 73, no. suppl 2 (September 2015): 83–96. https://doi.org/10.1093/nutrit/nuv045.

Bunn, D, O Jimoh, S Howard-Wilsher, and L Hooper. "Effectiveness of External Factors to Reduce Dehydration Risk in Older People Living in Residential Care: A Systematic Review," n.d.

Bunn, Diane K., and Lee Hooper. "Signs and Symptoms of Low-Intake Dehydration Do Not Work in Older Care Home Residents—DRIE Diagnostic Accuracy Study." *Journal of the American Medical Directors Association* 20, no. 8 (August 1, 2019): 963–70. https://doi.org/10.1016/j.jamda.2019.01.122.

Cheuvront, Samuel N, Brett R Ely, Robert W Kenefick, and Michael N Sawka. "Biological Variation and Diagnostic Accuracy of Dehydration Assessment Markers." *The American Journal of Clinical Nutrition* 92, no. 3 (September 2010): 565–73. https://doi.org/10.3945/ajcn.2010.29490.

Cheuvront, Samuel N, and Robert W Kenefick. "Dehydration: Physiology, Assessment, and Performance Effects." *Comprehensive Physiology* 4 (2014).

"Designing For Wearable Devices: Aspects to Consider," September 11, 2019. https://www.appventurez.com/blog/wearable-designing.

designnews.com. "6 Considerations for Designing a Wearable Device," November 12, 2016. https://www.designnews.com/6-considerations-designing-wearable-device.

Gartner. "Gartner Survey Shows Wearable Devices Need to Be More Useful." Accessed May 18, 2023. https://www.gartner.com/en/newsroom/press-releases/2016-12-07-gartner-survey-shows-wearable-devices-need-to-be-more-useful.

Gray, Martha, Judith S. Birkenfeld, and Ian Butterworth. “Noninvasive Monitoring to Detect Dehydration: Are We There Yet?” *Annual Review of Biomedical Engineering* 25, no. 1 (June 4, 2023): annurev-bioeng-062117-121028. https://doi.org/10.1146/annurev-bioeng-062117-121028.

Hooper, Lee, Asmaa Abdelhamid, Natalie J Attreed, Wayne W Campbell, Adam M Channell, Philippe Chassagne, Kennith R Culp, et al. “Clinical Symptoms, Signs and Tests for Identification of Impending and Current Water-Loss Dehydration in Older People.” Edited by Cochrane Kidney and Transplant Group. *Cochrane Database of Systematic Reviews*, April 30, 2015. https://doi.org/10.1002/14651858.CD009647.pub2.

Kickstarter. “LVL – The First Wearable Hydration Monitor,” November 11, 2019. https://www.kickstarter.com/projects/lactate-threshold/lvl-the-first-wearable-hydration-monitor.

La Gioia, Alessandra, Emily Porter, Ilja Merunka, Atif Shahzad, Saqib Salahuddin, Marggie Jones, and Martin O’Halloran. “Open-Ended Coaxial Probe Technique for Dielectric Measurement of Biological Tissues: Challenges and Common Practices.” *Diagnostics* 8, no. 2 (June 5, 2018): 40. https://doi.org/10.3390/diagnostics8020040.

Lacey, Jonathan, Jo Corbett, Lui Forni, Lee Hooper, Fintan Hughes, Gary Minto, Charlotte Moss, et al. “A Multidisciplinary Consensus on Dehydration: Definitions, Diagnostic Methods and Clinical Implications.” *Annals of Medicine* 51, no. 3–4 (May 19, 2019): 232–51. https://doi.org/10.1080/07853890.2019.1628352.

Liska, DeAnn, Eunice Mah, Tristin Brisbois, Pamela L. Barrios, Lindsay B. Baker, and Lawrence L. Spriet. “Narrative Review of Hydration and Selected Health Outcomes in the General Population.” *Nutrients* 11, no. 1 (January 1, 2019): 70. https://doi.org/10.3390/nu11010070.

Meaney, Paul M, Andrew P Gregory, Neil R Epstein, and Keith D Paulsen. “Microwave Open-Ended Coaxial Dielectric Probe: Interpretation of the Sensing Volume Re-Visited.” *BMC Medical Physics* 14, no. 1 (December 2014): 3. https://doi.org/10.1186/1756-6649-14-3.

“Microwave Dielectric Spectroscopy Workshop ‘Measure the Difference,’” n.d.

NHS. “Dehydration.” nhs.uk, December 19, 2017. https://www.nhs.uk/conditions/dehydration/.

“Our Wearable Future, Part 1: What Will New Tech Look Like?” Accessed May 18, 2023. https://www.webmd.com/a-to-z-guides/news/20220823/wearables-what-will-new-tech-look-like.

Patently Apple. “One of the next Health Features That May Be Coming to Apple Watch Relates to Tracking Hydration Levels of a User.” Accessed May 15, 2023. https://www.patentlyapple.com/2021/08/one-of-the-next-health-features-that-may-be-coming-to-apple-watch-relates-to-tracking-hydration-levels-of-a-user.html.

Porter, Emily, and Martin O’Halloran. “Investigation of Histology Region in Dielectric Measurements of Heterogeneous Tissues.” *IEEE Transactions on Antennas and Propagation* 65, no. 10 (October 2017): 5541–52. https://doi.org/10.1109/TAP.2017.2741026.

“Recognizing_the_face_of_dehydration.10.Pdf,” n.d.

Savoie, Félix-Antoine, Robert W. Kenefick, Brett R. Ely, Samuel N. Cheuvront, and Eric D. B. Goulet. “Effect of Hypohydration on Muscle Endurance, Strength, Anaerobic Power and

Capacity and Vertical Jumping Ability: A Meta-Analysis." *Sports Medicine* 45, no. 8 (August 2015): 1207–27. https://doi.org/10.1007/s40279-015-0349-0.

Shaheen, Naila A., Abdulrahman A. Alqahtani, Hussam Assiri, Reem Alkhodair, and Mohamed A. Hussein. "Public Knowledge of Dehydration and Fluid Intake Practices: Variation by Participants' Characteristics." *BMC Public Health* 18, no. 1 (December 2018): 1346. https://doi.org/10.1186/s12889-018-6252-5.

Sullivan, Scott. *Designing for Wearables : Effective UX for Current and Future Devices*. First edition. Sebastopol, California : O'Reilly, 2017.

Taylor, Kory, and Elizabeth B. Jones. "Adult Dehydration." In *StatPearls [Internet]*. StatPearls Publishing, 2022. https://www.ncbi.nlm.nih.gov/books/NBK555956/.

Valencell. "National Wearables Survey Reveals Accuracy Is Top Priority Among Consumers; Lack of Continually Interesting Insights Among Top Reasons for Discontinued Use." Accessed May 18, 2023. https://www.prnewswire.com/news-releases/national-wearables-survey-reveals-accuracy-is-top-priority-among-consumers-lack-of-continually-interesting-insights-among-top-reasons-for-discontinued-use-300289165.html.

Vega, Roy M., and Usha Avva. "Pediatric Dehydration." In *StatPearls [Internet]*. StatPearls Publishing, 2022. https://www.ncbi.nlm.nih.gov/books/NBK436022/.

"Wearable Devices for Non-Invasive Sensing." Accessed May 18, 2023. https://encyclopedia.pub/entry/7146.

Weinberg, A. D., and K. L. Minaker. "Dehydration. Evaluation and Management in Older Adults. Council on Scientific Affairs, American Medical Association." *JAMA* 274, no. 19 (November 15, 1995): 1552–56. https://doi.org/10.1001/jama.274.19.1552.

Thank you for reading!