

MenstruPal: A Smart Sensor to Monitor Menstrual Rhythm

*A Thesis Presented To
The Academic Family*

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*To,
My parents, who brought me into this world,
Shri Dilip Mukherjee and Smt. Bula Mukherjee,
The ones whom I brought into this world,
Rishika Bhakat and Shrihaan Bhakat,
The one who has been with me all the time, my better half
Amrit Bhakat*

Certificate

This is to certify that the thesis titled **MenstruPal: A Smart Sensor to Monitor Menstrual Rhythm**, submitted by **Manideepa Mukherjee**, to the Indraprastha Institute of Information Technology, Delhi, for the award of the degree of **Doctor of Philosophy**, is a bonafide record of the research work done by her under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.



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Declaration

This is to certify that the thesis titled **MenstruPal: A Smart Sensor to Monitor Menstrual Rhythm**, submitted by me, to the Indraprastha Institute of Information Technology Delhi for the award of the degree of **Doctor of Philosophy**, is a bonafide work carried out by me. This research work has been carried out under the supervision of **Prof. Aman Parnami**. The study pertaining to this thesis has not been submitted in part or in full, to any other University or Institution for the award of any other degree.



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Abstract

Ubiquitous health monitoring systems are gaining a lot of interest due to their potential to provide continuous, real-time information via non-invasive measurements of physiological parameters. Menstruation is a periodic biological process that is essential for women's health. In this report, we described a textile-based blood volume sensor that can be integrated into the sanitary napkin to quantify menstrual blood loss during menstruation. Through benchtop characterization tests with 5 mL of saline fluid, we determined the effect of spacing, orientation, weight, and location of fluid drop on the sensor. The sensor has been evaluated by intravenous blood samples collected from 18 participants and menstrual blood samples collected from 10 participants for four months. The collected intravenous blood samples and menstrual blood samples were used to create two regression models that can predict the blood volume and menstrual blood volume from the voltage input with Mean Absolute Percentage Error (MAPE) of 11-15% and 15-30%, respectively. We also presented a modified design of the sensor and the result of a 10 participants user study to evaluate the effect of activities performed by the users. We showed that the sensor performs uniformly for all activities across the users. Through a user experience study, we found that the wearable sensing system is comfortable and safe to use. Further, we explored the design of a battery-less wearable sanitary napkin system to test the feasibility of data collection using an NFC-enabled smartphone.

Contents

1 Introduction	8
1.1 Research Statement and Research Questions	11
1.2 Contributions	13
1.3 Research Findings	13
1.4 Organization	14
2 Literature Review	16
3 Design of Menstrual Blood Loss Volume Sensor	27
3.1 Interviews with Healthcare Practitioners	28
3.2 Sensor Design	30
3.3 Parameter Testing	32
3.3.1 Spaces Between Conductive Traces	32
3.3.2 Orientation	34
3.3.3 Weight	35
3.3.4 Fluid Dropping Location	36
3.4 Testing With Other Saline solutions	39
3.5 Testing With Intravenous Blood	40
3.6 Testing With Menstrual Blood	43
3.6.1 Testing On One Location	46
3.6.2 Testing With Large Volume	47
3.7 Prediction Model For Intravenous Blood	49

3.7.1 Prediction Model For Menstrual Blood	52
3.8 Discussions	54
3.9 Limitations	56
3.10 Summary	57
4 Characterizing The Effect Of User Activities On Sanitary Napkin-Based Bod-	
ily Fluid Monitoring	59
4.1 Wearable Sensor Design	60
4.2 Pilot Studies	63
4.2.1 Pilot Study On Benchtop Setup	63
4.2.1.1 Setup	63
4.2.2 Experiment Method	64
4.2.3 Pilot Study With Mannequin	64
4.2.3.1 Setup	64
4.2.3.2 Experiment Method Update	65
4.2.3.3 Results and Analysis	65
4.3 Six-Thread Sensor Design	66
4.3.1 Benchtop Experiment To Compare The Six-Thread Design With Two-	
Thread Design	67
4.3.1.1 Setup	67
4.3.1.2 Experiment Process	68
4.3.1.3 Results and Analysis	68
4.3.2 Experiments with Mannequin	68
4.3.2.1 Setup	69
4.3.2.2 Experiment Method	69
4.4 User Studies	69
4.4.1 Study 1: Effect Of Activities	69
4.4.2 Participants And Setup	70

4.4.3	Procedure	71
4.4.4	Observations	72
4.4.5	Results and Analysis	73
4.5	Study 2: User Experiences From Wearing The Sensor Pad	73
4.5.1	Methods	75
4.5.2	Analysis	75
4.6	Limitations	76
4.7	Discussions	77
4.8	Summary	78
5	Exploration of Battery-less Wearable Sanitary Napkin System Design	79
5.1	Wearable Sensor Design Using NFC Technology	80
5.2	Mobile Application	81
5.3	Pilot Studies With Fabric Materials and Layers	82
5.3.1	Experiment Setup	83
5.3.2	Experiment Method	83
5.3.3	Results	83
5.4	Pilot In-The-Wild Study With Menstruating Participants	84
5.4.1	Process	84
5.4.2	Findings & Discussions	85
6	Discussions	87
7	Future Work & Conclusions	92
7.1	<i>Restatement of the Thesis Statement, Research Questions and Contributions</i>	92
7.2	Contributions	93
7.3	Critical Reflection	94
7.3.1	Restricted Data Collection	94
7.3.2	Characterizing Complex Activities In a Day	94

7.4 Open Challenges & Opportunities for Future Research	95
7.4.1 In-The-Wild Study With Menstruating Users	95
7.4.2 Fluid Property Variation	96
7.4.3 Alternative Design Considerations	96
7.4.3.1 Sustainable Design	96
7.4.3.2 Alternative Methods of Design	97
A Matlab Code	124
B Microcontroller code	129

List of Figures

2.1 Applications with the features they provide.	21
2.2 Metrics available in popular applications	22
3.1 (a) Layers present in disposable sanitary napkin, (b) Circuit for parameter testing	31
3.2 Experimental setup for Space testing	32
3.3 Schematic of the setup for space testing	33
3.4 Output Current change with the added volume of Normal Saline	34
3.5 Comparison of currents on curved surface, applied weight on sensor with flat	
surface without weight	34
3.6 Setup in use	35
3.7 (a) Prototype, (b) Fluid dropped location for orientation change, (c) Final pro-	
totype with weight	35
3.8 Location of stain at sleeping position	37
3.9 Location of stain at sitting position	37
3.10 Comparison of currents with 3:2 and 4:1 proportion of fluid dropped at different	
location	38
3.11 Fluid dropped location for different locations with upright and slanted positions	38
3.12 Comparison of output voltage with the volume of fluid dropped	40
3.13 nRF52832 SparkFun Breakout Board Microcontroller	41
3.14 Sensor circuit integrated into the napkin	41
3.15 Intravenous Blood sample	42
3.16 Standard deviation of Blood samples	43

3.17 Menstrual Cup with markings on it	45
3.18 Comparison of average output voltages of one location experiments with two location experiments using Menstrual Blood	47
3.19 Comparison of output voltages of one location with Menstrual Blood, one location with Intravenous Blood, large volume with Menstrual Blood	48
3.20 Standard deviation of Menstrual Blood samples	49
3.21 (a) Intravenous Blood Boxplots for Models M1:Gaussian Process Regression (Mattern 5/2) M2:Gaussian Process Regression Exponential M3:SVM (Fine Gaussian) M4:Tree (Fine Tree), (b) Predicted volume and Ground Truth Value after testing on SVM Fine Gaussian Model	51
3.22 (a) Menstrual Blood Boxplots for Models M1:Gaussian Process Regression (Mattern 5/2) M2:Gaussian Process Regression Exponential M3:SVM (Fine Gaussian) M4:Tree (Fine Tree), (b) Predicted Volume of Menstrual Blood and Ground Truth Values after testing on SVM Fine Gaussian Model	53
4.1 Different Types of Pressure Applied on the Napkin	61
4.2 Experimental Setup	64
4.3 Sanitary Napkin Setup for Testing With Mannequin	65
4.4 Benchtop Experiment with Two-thread Design	65
4.5 Pilot Study with Two-Thread Design with Mannequin	66
4.6 Six-Thread Sanitary Napkin Sensing System	67
4.7 Schematic Diagram of the Sanitary Napkin Sensing System	67
4.8 Comparison of the Six-Thread Design with Two-Thread Design on Benchtop Setting	68
4.9 Experiment with Six-Thread Design on Mannequin	69
4.10 Activities Performed by the User	71
4.11 Analysis Across Activities	73
4.12 Interpersonal Variation of Sitting and Standing Activity	74
4.13 Interpersonal Variation of Walking and Lying Down Activity	74

5.1 PCB and the NFC Antenna Connected	81
5.2 3D Printed Casing Closed and Open View	81
5.3 Prototype of the Battery-less Wearable Sanitary Napkin System	81
5.4 User Wearing The Battery-less Sanitary Napkin system	85

Chapter 1

Introduction

Self-tracking wearable sensors are ubiquitous today for monitoring physiological conditions privately. The current trend in modern healthcare is that individuals actively participate in health promotion and follow their own state of health. Recent Covid 19 outbreak made this a mundane activity to observe biological signals such as Sweat [1], pulse rate [2], SpO2 [3], glucose [4], sodium [5], Calcium and pH [6] etc. regularly. Several works on sensing devices [7,8] have been shown to collect many physiological information such as heart rate [9], sodium (135-147 mmol/L) [5], glucose (45-96 mg/dL), sweat rate [10], pH [6] etc. for self-monitoring. However, we still lack a sensing system for monitoring menstrual health, which plays an important role in the physical, psychological, and social well-being of a woman. Even though many mobile applications such as [helloclue](https://helloclue.com/)¹, [flo](https://flo.health/about-us/)² have been gathering menstrual health information from self-reported data from the user, these reports are heavily influenced by mental and physical conditions of the women. Automatic data collection through a sensor would reduce these biases and give a better estimate of health conditions.

Menstruation is a periodic physical phenomenon in every woman between puberty and menopause, where a woman loses 35-60 mL of blood every 28-35 days. Abnormal Uterine Bleeding (AUB) is a clinical problem where women experience heavy menstrual bleeding of about 80-100 mL of blood. This can be a symptom of underlying health conditions such as

¹<https://helloclue.com/>

²<https://flo.health/about-us/>

cervical cancer, uterine fibroid, etc. [11]. Approximately 30% of women face this problem in the reproductive age of 30 to 45 [12,13]. Excessive bleeding is the main presenting complaint in women referred to by gynecologists, and it accounts for at least 30% of hysterectomies performed in the USA [14]. AUB interferes with a woman's physical, emotional, social, and material quality of life [15] and understanding AUB is also important currently to guide treatment [16]. This may cause anemia [17], lead to limitations in social, physical, and leisure activities [18,19], and be associated with increased healthcare resource use and cost [20]. However, as suggested by the previous researchers, self-perception of heavy menstrual bleeding can be inaccurate [21], and this may result in surgical interventions which are distressed by menses that are actually defined as low volume. Questionnaires on menstrual health are also found inappropriate for use [22], and there are no recommendations for quality of life tools [16,23,24]. Evaluation of Menstrual Blood Loss (MBL) informs patient choice by providing context and clarity; for example, the finding of MBL within the normal range may reassure a woman with perceived heavy menstrual bleeding to the extent that they decide not to seek further treatment [25-28]. Also, measurement of MBL can be helpful when establishing the etiology of cases of anaemia, and changes in MBL are often important to evaluate treatment efficacy in clinical trials.

Based on the discussion with the gynecologists, we identified that regular menstrual bleeding and menstrual cycle are the two important criteria of menstrual health. Menstrual blood loss volume detection is more challenging than menstrual cycle tracking, as well as important as the blood is already absorbed in the sanitary napkin. Also, the user or the expert does not have any reliable way of measuring it without a clinical setting.

There are social, psychological, informational, as well as technical challenges associated with menstrual health monitoring. In many parts of the world, it is taboo to talk about menstruation. This lack of openness hinders redressing of menstruation-related misconceptions, prevents its treatment as a natural phenomenon and, consequently, leads to ignorance of any early signs of irregularities and its consequences. Inadequate information about symptoms of menstrual diseases and menstrual health management further delays early diagnosis. Moreover, vital information on menstrual health is lost with the disposal of sanitary products.

On the technical front, prior medical research [29–32] has tried to quantify menstrual blood loss using different methods, for example, pictorial chart [29] and weighing of sanitary products [31]. Most of these require the collection of used sanitary napkins from the participant. The process of analyzing the data also takes hours. Additionally, the analysis is not done in real-time. Besides, commercial products such as sanitary napkins and tampons that are available to absorb menstrual blood only suffice the need for managing the menstrual cycle, not detecting physiological parameters that help identify women’s different health conditions.

Apart from these challenges associated with menstrual blood volume measurements in general, wearable systems are very susceptible to physiological, environmental noises, and motion artifacts [33,34]. Physiological differences of each individual, variations in activities performed by the wearer, and body posture always affect the sensor data collection of the wearable system. The lower body shape, body weight, height, and variation of fluid parameters such as fluid volume and fluid properties are distinct for each individual. Moreover, the various activities performed by each person are unique in their own way. Characterization of each of these variables is necessary to understand the effect of these parameters. However, the menstrual blood loss measurement is even more complex as no biological reference is available to verify the system.

From the HCI perspective, very little work engages with body materials, particularly menstrual blood. To our knowledge, no prior research describes a wearable sensor to measure menstrual blood volume from a sanitary napkin, the topic of this thesis research. Through this thesis, we aim to solve the engineering and methodological challenges by describing the design methods and process of working with intimate body materials. We understand that menstruation is a phenomenon that has social connotations; for women, it has personal significance and clinical significance. Though we could contribute to the other aspects, our approach complements discussions or debates around menstruation and women’s health; it also adds methodological contributions to the HCI research on taboo topics involving intimate aspects of participants’ lives. It faced ethical challenges such as building rapport and blurring boundaries with the participants, privacy, etc., while conducting this research, and in a small and

significant way, it contributes to how such research could be conducted in the future. Overall this thesis contributes to creating objective measures and information gathering on menstrual health, women’s self-reflection, and tools and methods for quantified self.

1.1 Research Statement and Research Questions

Based on the identified opportunities, our research statement is as follows.

A sanitary napkin sensor for women can help in monitoring the menstrual blood loss volume.

We further break down each aspect of this statement into research questions that drive an independent investigation to provide justification for our claim. In this report, consider the following research questions.

- **RQ1** Can a sanitary napkin sensor be designed to measure the menstrual blood loss volume? (Chapter 3) [35](#)
- **RQ2** What effect do the activities performed by the user have on a minimally invasive, wearable sanitary napkin system built for the measurement of bodily fluid? (Chapter 4)
- **RQ3** Is it technically feasible to create a battery-less wearable sanitary napkin system design for in-situ data collection? (Chapter 5)

RQ1 We address the first research question by the following research methodologies

Survey With Gynecologists & Female Participants

We interviewed five gynecologists to identify what type of gynecological issues are faced by women in the age range of 20-35, how frequently they visit a gynecologist and the type of questions asked by them. To gather more information, we interviewed five females who had faced menstrual health issues earlier. To collect more information, we talked to them separately about the changes they observed in their menstrual cycle and necessary diagnostic tests, medicine, and lifestyle changes prescribed by the doctors for further treatment. Further, we surveyed female participants to understand the preferable brand and size of the napkin.

From these initial formative studies, we understand that menstrual blood volume and the regular menstrual cycle are two critical indicators of menstrual health.

Design of the Sanitary Napkin Sensor We used iterative design methodologies to design the sanitary napkin sensor. Through benchtop testing with 5 mL of fluid, we determined the effect of spacing between the conductive threads, orientation, and weight on the sanitary napkin sensor.

Evaluation We evaluated our sensor using three different kinds of fluid saline, intravenous blood, and menstrual blood on a benchtop setting.

RQ2 We address the second research question by the following methodologies

Redesigning the Prototype We redesign the sanitary napkin system to make it a wearable system for testing on mannequins and on users. We also extended the design from a two-thread design to a six-thread design to resolve the issue of side pressure applied on the napkin by the legs.

User Studies We conducted an extensive user study with ten female participants for the four different activities. For this user study, we recruited participants aged 19 to 35 years and conducted user studies with various activities standing, sitting, walking, and lying down. For each activity, the average duration of using the wearable sanitary napkin system was approximately one hour. We also performed another user study with the participants to understand the experience of the participants with the wearable sanitary napkin system.

RQ3 We address the third research question by the following methodologies.

Battery-less Sanitary Napkin System Design We designed the battery-less sanitary napkin system with a sanitary napkin sensor and a wearable data collection module. To collect and store data from the sanitary napkin system for further analysis we developed a mobile application. We used NFC technology to power the sensing system and to communicate the data to the NFC-enabled smartphone.

Experimental Evaluation We conducted benchtop experiments to understand the effect of various fabric materials on the NFC communication range. We also experimented with different layers of fabric material to understand its effect on NFC communication and data

collection.

User Study We conducted a pilot user study with menstruating users to test the technical feasibility of the battery-less sanitary napkin system.

1.2 Contributions

In this report, we make the following contributions:

- Design and evaluation of an absorbed blood volume sensor with a resolution of 0.5 mL embedded in an off-the-shelf sanitary napkin.
- Investigation of different sensor parameters such as proper spacing to detect the output, effect of orientation, and weight on the sensor.
- A model for prediction of intravenous blood volume from the output voltage created using blood data of 18 participants.
- A model for predicting menstrual blood volume from the output voltage was created using 40 menstrual blood data collected from 10 participants.
- Design of a wearable sanitary napkin system that helps to monitor the effect of different activities performed by the user.
- Insights collected from the in-the-wild study with saline for different activity on the sensor for all users.

1.3 Research Findings

The key findings from this thesis are the developments and evaluations of sanitary napkin sensing systems in different settings. We designed a sanitary napkin sensor and tested it in multiple benchtop settings to determine the effect of spacing, orientation, and weight. We evaluated it

using different kinds of saline liquids, intravenous blood, and menstrual blood. Since the benchtop characterization can not capture the effect of on-body variations and activities, then we designed a wearable sanitary napkin sensing system to understand the effect of different user activities on the sensor. Our results showed that the voltage output increases with the increase in the amount of fluid volume. This direct relationship between the voltage and the fluid dropped motivated us to construct a model which can predict the volume of the fluid using the change in voltage detected by the sensor. From the SVM Fine Gaussian Model that we have constructed using machine learning, we are able to predict the volume values with the mean absolute percentage error of 11-15% for intravenous blood and 15-30% for menstrual blood. This motivated us to create a wearable sanitary napkin system to conduct in-the-wild studies with female participants to understand the effect of activities like standing, sitting, walking, and lying down. We identified that the effect of activities remains uniform for all cases, and the trends remain the same as the benchtop experiments. The study of the experience of wearing sanitary napkin sensors identified that this would be a valuable technology for females. We also explored the direction of developing an end-to-end battery-less wearable sanitary napkin system design to test the feasibility of in-situ data collection with menstruating users. Through pilot studies with different fabric materials and a few users, we identified that this kind of system design is possible.

1.4 Organization

Chapter 2 presents a survey of relevant literature on women’s health and technologies in HCI, Mobile technologies in menstrual health, sensors for bodily fluid sensing and systems, and clinical methods of menstrual blood loss monitoring. Chapter 3 presents the design, implementation, and benchtop evaluation of the sanitary napkin sensor MenstruLoss to measure menstrual blood loss volume. Based on the insights gathered from the design of the sensor, Chapter 4 presents the design and development details of the intelligent sanitary napkin system and user studies to characterize the effect of different activities on the sensor. Chapter 5

presents the exploration of batteryless sanitary napkin sensor design, followed by discussions in Chapter 6. Finally, we present the future work and conclusions in Chapter 7.

Chapter 2

Literature Review

There has been increasing attention in Human-Computer Interaction (HCI) towards designing technologies that can positively impact women’s health in practising reproductive, sexual, maternal or overall physical health. Not only from the need to address women’s concerns but also from other aspects such as safety and security [36-38], democracy, political activism [39,40].

We situate our work in prior research by summarizing the broader view of women’s health in HCI and how different technologies are being used to engage women with their bodies and healthcare. Next, we present how various mobile applications and technologies collect women’s health information and the different reasons for using them in personal health tracking. Finally, we summarise the prior research in body fluid monitoring and clinical methods to measure menstrual volume, thereby highlighting the need for a system to track menstrual health effectively in a private setting.

Women Health and Technologies in HCI

Our research focuses on women’s menstrual health, which binds itself with areas such as digital technologies, women’s healthcare, and menstruation, and all these areas come under the umbrella of Women’s Health and Technologies in HCI. However, the broader goal of our research is to advance technical knowledge by creating an interactive sanitary napkin as well as to engage with topics that are currently neglected in current HCI research. We identified a few themes

that reappear in previous research in the context of women’s personal care and technologies - 1. Technologies to empower and engage women with their bodies at different life stages, 2. Technologies to educate women about menstrual health and changing physiology, 3. Issues, trouble, and challenges related to menstruation and intimate health research. In this section, we present the discussion in previous research on these topics and show how our research engages with them.

There are multiple ways technologies have been connected to women’s personal care and health in previous literature. HCI community used women-centered design [41,42] methodologies for developing female-friendly digital technologies [43,44]. Digital technologies have been designed to support the better experience of menarche [45], intimate touch [44], motherhood [46] sexual well being [47,48] and pelvic floor exercise [49]. These previous researches identified the need to pay attention to the different living conditions of women and how HCI technologies can be built around them. Researchers have designed Toolkits with textile materials and electronics for intimate health literacy [50] and menstruations [41]. These attempts are made to engender conversations on the intimate body and care. One other research has investigated how the body’s materiality - its anatomy and physiology and other material forces actively matter to the processes of materialization [51]. Earlier research attempted to engage women with various female bodily fluids such as menstrual blood, saliva, and cervical mucus through research through a design project [52]. The authors showed that touching and looking at bodily fluids led to creating new knowledge of self and changing body. This work also highlighted various frictions faced by the participants within themselves, their home, and their social surroundings because of the societal stigma and preconceptions about menstruation and how self-touch can contribute to reconfiguring the way menstruating bodies are treated in society. These interventions empower and educate women using different materials and methods, while our work concentrates on informing women, using actual body material, and providing true measures of their body material - menstrual blood.

Another bunch of research explored mobile applications and games to educate females, and adolescent girls about menstruation and well-being [53]. Jain et al. designed a tablet-based

game HelpPinky to teach adolescent girls in Assam, India, about menstrual health and related myths [54]. Similarly, an IoT-based working model of the uterus was built by Tran et al. to engage children and parents in early discussions on menstrual health. [55]. MenstrualMaze [55], and MenstrualMonster [56] are coeducational interactive games for teenagers to educate them on menstruation. Their user study with male and female teenagers identified the motivation differences related to gender and showed an observable change in the attitude towards menstruation. "*Designing menstrual technologies with adolescents*" [57] focused on designing technologies to educate girls about the physiological changes in menstruation and the physical experiences of the menstrual cycle, such as abdominal pain and menstrual cramp. Through a workshop, the authors identified the different feelings and experiences of participants during menstruation, such as depressive and anxious feelings before the menstrual cycle and pain, and created technologies to respond to their experiences using shape-changing actuators and heat pads. These design-led efforts attempt to address menstrual taboo, to engage and encourage communities, parents, and teenagers with a taboo topic, and to create technologies for positive menstrual experiences. Our work also encourages conversation around the symptoms and markers for menstrual health and well-being from a different dimension and technological perspective. Along with educating women, teenagers, and adolescents about menstruation and changing bodies, it is also essential to consider the signs and symptoms of female health conditions and living.

Apart from technologies and education related to women's health and menstruation, there is growing interest in the HCI research communities about how the social connotations, taboos, and perception makes it difficult and challenging to conduct research and practice on this topic [44]. Several research has explored the areas related to trouble faced by women during different life stages and how to navigate them. For example, a recently published article called *Troubling Design* [58] by Marie et al. discussed the problems women face while undergoing different body transitions and the researchers who design technologies for them. Tuli et al. discussed the different struggles faced by women during traveling during menstruation and how safe space is conceptualized by women where they can manage their menstruation [59].

Through interviews and participatory design, the authors investigated how women deal with their periods on the go. Previous research also suggested that, in designing for intimate care and other sensitive topics related to women’s health, designers should focus on channeling the experiences and emotions of women [44]. Many other research [60–63] focused on how social-cultural beliefs, shame, and embarrassment associated with menstruation create hindrances in menstrual health management practices. These previous efforts identified various gaps and challenges associated with this topic and why this research area has not been explored much, whereas we also identified several engineering, methodological and other challenges that are associated with objective menstrual health research.

Since research on sensitive topics like menstruation is often shaped by locally situated cultural taboos, discussion, and education, therefore, the design, process, and implementation methods also change with the ecology and culture, and the solutions may vary depending on the context and demographics. Our work on the menstrual volume measurement system supports the ongoing discussion of women’s menstrual health by enabling them to collect, observe and share information that helps them see the ongoing changes in their bodies. The description, design details, methods, user studies, and practices outlined in this thesis can be used as a template and foundational contribution to the field of designing personal care interventions. However, digital technologies should enable, empower and educate every woman irrespective of social structure, education, and financial conditions. Our research also encourages discussions on making electronic and digital research matter to underserved communities with low-literate females in difficult financial conditions.

Mobile Technologies In Menstrual Health

Although our research in this thesis is centered on quantitative menstrual measures, it also allows users to track true menstrual volume over time from the wearable sanitary napkin system by transferring the data to mobile devices. Therefore, we reviewed previous research in this direction to understand the limitations and gaps in this domain and the various exist-

ing mobile applications that gather subjective menstrual health-related information. Epstein et al. presented an extensive analysis of user engagement with tracking applications across the United States [64]. Since then, researchers have looked at different transitions and tracking needs for the menstrual journey, i.e., menstrual tracking (e.g., [64, 65]), fertility tracking (e.g., [66–68]), and menopausal tracking (e.g., [69, 70]). Earlier research has found the limitations of various assumptions and biases in the design of menstrual tracking apps, including the non-inclusion of sexual and gender minorities, the conflation of menstrual tracking and fertility planning, and non-consideration of women’s life transitions — young adulthood, pregnancy, and menopause [64, 65, 71]. These design implications are important to consider for developing wearable technologies and trackers because, with different life stages, gender, and sexual minorities, the purpose, reason, and uses of these technologies vary. We provided the metrics (see figure 2.2) that are collected by these mobile apps and which clearly show the metrics that are not suitable for some stages; for example, menstruation information may not be suitable to collect during pregnancy. We are building a wearable system for menstruating users, these design implications are also important for us, and we are consuming these insights for building our system.

Multiple previous research aimed to figure out the various purpose of menstrual tracking and how it affects different ecologies. In [72], the authors have considered why and how women track their menstrual cycles to exploit opportunities in designing such systems for women. This work concluded that women track their cycles for various reasons, like remembering and predicting their periods and becoming a part of the forums provided by some of these applications. The authors also noted that the existing applications fail to consider a woman’s life stages. The paper encourages the expansion of personal informatics. Another work examined how menstrual tracker is being used across ages of women and how it can enable period buoyant ecologies [73]. There are various aspects of menstrual tracking, as above, and our research adds a new dimension to this tracking by augmenting true volume measures. Together with these already existing health metrics collected by the menstrual trackers, our actual menstrual volume information can provide a holistic view of a woman’s health conditions and well-being. We

synthesize a list of mobile applications and the various features of those applications, such as data visualization, export operation, the purpose of app usage from the user, blogs and forums, and backup. We categorized the mobile applications based on the health information it collects from users, such as sleep duration, feelings, cervical mucus texture, etc. Figure 2.1 summarizes the features of some of the significant applications. Some of the health metrics used in these applications are shown in figure 2.2.

Name	Integration with other apps	No. of tracking categories	Data visualizations	Export health data	Asks for purpose of using app	Blogs/forum	Backup data to google account
Clue	Apple Health		31 charts/graphs	yes	yes	widely used	yes
Eve	None		26 Circular chart for only next date	No	No	proper community	No
Flo	Google Fit, Fitbit		43 graphs for each categories	No	Yes	Yes	No
Period Tracker	none		58 .txt file exported to doctor	Yes	no	yes	Yes
Pink Pad Pro	none		5 charts	No	yes	yes	no
Glow	none		18 Appealing	No	Yes	Yes	No
Ela	none		10 charts for weight and temp/premium	yes	yes	yes/doctor consultation	no
My Calendar	none		40 graphs	yes	yes	yes	yes
Maya	Calendar(premium)		25 graphs for each	no	yes	yes/ expert advice	yes(premium)
P Tracker	none		20 charts/calendar	invite partner/mail	yes	no	no
Pepapp	none	none	simple chart	no	yes	Widely used blogs	No
Period Diary	none	1(temperature)	calendar	no	no	yes	yes
Ovia Fertility	fitbit ,jawbone ,withings		15 graphs for each	no	yes	yes	no
LadyTimer	none		13 charts for each categories	yes	yes	No	yes
P.D.	none		20 appealing ui	no	yes	yes	no
Fertility Calendar	none	1(temperature)	calendar	no	no	no	no
Cycle Beads	none	none	calendar/cycle view	no	yes	no	yes
My Period Tracker	none		18 pie chart	no	yes	Widely used blogs	yes

Figure 2.1: Applications with the features they provide.

Body Fluid Sensing System

Several prior research has focused on developing devices that monitor physiological parameters such as sodium [5], pH level [74], sweat rate [75], body temperature [76] using various sensing technologies and materials [77]. One such example is the garment-integrated leak detection system described by Foo et al., which uses wetness sensing to detect the location of the leak from containment systems such as diapers or sanitary napkins [78]. Another paper monitors urine leakage and sends an alarm to the user using a vibrator system [79]. Linti et al. [80] designed a sensory baby vest for respiration, heart rate, temperature, and humidity to detect discomfort in infants. Many research on body humidity sensing using different techniques has also been studied [76, 81, 82]. Fabric-based or soft sensors are gaining increasing attention in wearable devices due to their comfort and garment-like feeling that is suitable for use for a

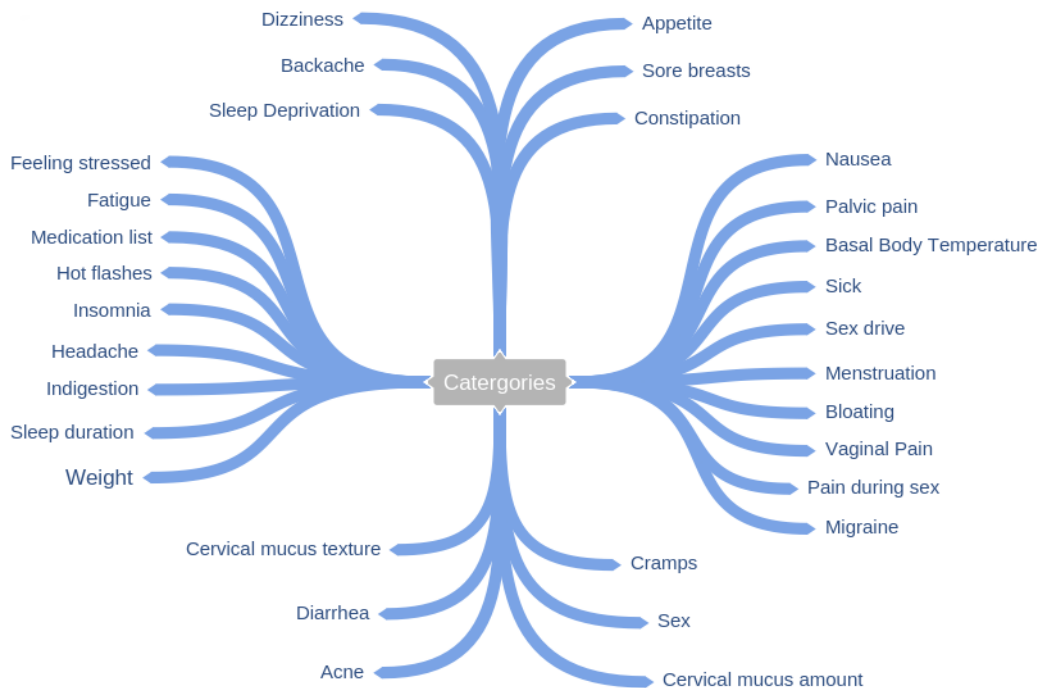


Figure 2.2: Metrics available in popular applications

longer duration than rigid electronic material. Many research already exists on soft health monitoring devices for monitoring respiration [83], sleep, heart rate [84], and other biological parameters [85]. While all these works are targeted toward general health monitoring, a few research attempts have started looking into diagnostics [86-88] using modified sanitary napkins to diagnose Chlamydia, Candida infection. These instrumented sanitary pads collect samples when the woman is not menstruating, and the sample needs to be sent for laboratory tests. However, a soft sanitary napkin that collects women’s body fluid every month with a lot of potential information about female health remained unexplored.

Prior research in this domain concentrated on sensing the physiological signals and biomarkers present in the body—our work focus on gendered body fluid. The menstrual fluid has different properties than the other body fluids present in the human body. Also, the limited access to menstrual fluid makes this research process and methods more challenging and unique. Our experiment process, data collection, evaluations, and user studies are distinctive from the existing previous research in the domain of body fluid sensing. Therefore, this creates new

opportunities for more research in this domain and female health monitoring devices.

Medical Research on Menstrual Blood Volume

Researchers published different ways of quantifying menstrual blood loss and gathering information from menstrual blood. The gold standard for measuring menstrual blood loss is the alkaline hematin technique, where sodium hydroxide is used to extract the hemoglobin from used sanitary napkins and convert it to hematin, then measured by spectrophotometer [89] to estimate the blood content. Several researchers modified this method to simplify and quicken the process using automatic extraction [90]. Michael et al. [30] showed how to measure menstrual blood loss in a routine setting by collecting sanitary napkins. The method explained in this paper is time-consuming and needs the patient to be present for the data collection one complete menstrual cycle. Another way of quantifying total menstrual blood loss was by weighing used menstrual products [31,91]. A body of researchers used a questionnaire [?,92] and menstrual diary [93] to quantify menstrual blood. Collecting data using pictorial blood loss assessment is still a widely accepted method [29]. To identify the best way of estimating the blood volume, researchers have compared and analyzed all these different methods [15,32,93].

The following sections provide the background on the clinicians' three widely used methods to measure Menstrual Blood Loss volume.

Alkaline Hematine Technique

The alkaline hematin technique is the gold-standard method of chemically measuring the blood content of used sanitary products, which was established in 1964, with later modifications [30,94-96]. In this method, the menstrual blood is extracted using an alkaline solution (Sodium Hydroxide), and then the hemoglobin content is measured to estimate the menstrual blood volume. However, this is an expensive procedure that requires specialized laboratory facilities. Patients must collect, store and then submit all their used sanitary products for MBL analysis, which may not be acceptable or feasible for many women. Therefore, it is mainly confined

to clinical trials and the research setting to confirm or refute HMB and evaluate the efficacy of medical or surgical treatments. Due to the practical limitation of this method, many new approaches to measuring MBL have been developed since the publication of the alkaline hematin method more than 60 years ago [97-99]. During this time, sanitary wear has evolved from cotton-based sanitary products to superabsorbent-polymer-containing (SAP-c) ultraslim towels containing granules [100]. There is a requirement to validate any method for measuring MBL with the same types/brands of sanitary products that the technique intends to use. With modifications to improve speed and usability, efficiencies of recovering various volumes of blood from a selection of sanitary products ranged from 74.8% [94] to 107% [101]. Adaptation of the method for a selected brand of SAP-c towels resulted in the recovery of at least 90% (85% with automation) of simulated menstrual fluid volumes has been described by Magnay et al. [95,102].

Estimation using Pad Count and Duration

Prior studies have investigated the association of menstruation with the duration of the cycle [26,103,104]. Since cycle duration is a piece of important information, this was requested in questionnaires [105,106], and this parameter forms part of both the PBAC and menstrual pictogram methods of assessing MBL [103,107]. However, in self-perceived heavy menstrual bleeding, period duration was not significantly different for the lightest versus the heaviest periods [21]. While Higham et al. and Warner et al. showed that MBL was associated with the total number of pads and tampons used [107,108], other studies found no significant or overall correlation between pad/tampon count and MBL [21,26,94,107,108]. Since the number of pads used, [106,109-114], frequency of changing pads [115-117] are important parameters for questionnaires these questions are included in further studies.

Pictorial Methods

Pictorial Blood Loss assessment charts (PBACs) are the most commonly used method to assess menstrual blood loss in clinical trials. It is a semi-quantitative method where the user can directly record the number of her used sanitary items and the level to which they are

bloodstained. This simple, inexpensive tool comprises a visual scoring system that depicts a graded series of soiled tampons and towels and is most widely used by medical practitioners for studies and treatment. Previous studies [118,119] have shown PBAC to measure postpartum blood loss. It can also be used to screen females for investigation of hemostatic disorders for which heavy menstrual bleeding may be an important symptom [120,121] and to evaluate the cost-effectiveness of different therapies for heavy menstrual bleeding [122,123].

While most of the medical methods of menstrual measurement require collecting and processing the used sanitary napkin or tampon, which is not feasible outside the medical setting, the other estimation methods are subjective. Different social and cultural biases make the estimation more challenging for practitioners. In countries like India and Global South, where menstruation is taboo, women do not want to share their privacy. The detection of menstrual issues at early stages is nearly impossible.

Except for physical issues, irregular menstrual bleeding can impact women's social, emotional, and physical well-being. Leaks and staining clothes are associated with embarrassment [124]. Studies showed that health-related quality of life changes with irregular menstrual bleeding [125]. Researchers studied that women generally act to comply with a strong social message that menstruation should be concealed. Though this behavior was often taken for granted, The need to hide evidence or reminders of menstrual bleeding was particularly important [126]. The menstruation symptoms create stress along with other physical signs of it. Previous research concluded that the social pressure to maintain concealment of menstruation strongly influences women's health-related behavior in response to menstrual concerns [126]. A previous study with 22 primary care professionals investigated that the combination of unhelpful medical definitions, lack of standards of normality, and difficulties in discussing menstruation resulted in individual practitioners making judgments in idiosyncratic ways [?]. In the absence of a useful gynecological model, practitioners develop individual, often subjective and gendered models to use in practice. Overall, they face problems in using current definitions of menstrual disorders.

Overall we identified several gaps, including the limitations of the measurement approach of

pictorial and weighing methods, constraints of alkaline hematin techniques, lack of availability of menstrual health monitoring sensing system, and suitable estimation methods. The rest of this thesis describes our attempts to fill these gaps through sanitary napkin sensor design, development, implementation, and evaluation. Our work in this thesis is a stepping stone towards personalized menstrual tracking where data sharing could be possible with clinicians as and when required.

Chapter 3

Design of Menstrual Blood Loss

Volume Sensor

Based on the identified limitations of menstrual volume measurement and the need for regular menstrual tracking, we formed our first research question **Can a sanitary napkin sensor be designed to measure the menstrual blood loss volume during use?**

This chapter presents MenstruLoss: A sanitary napkin-based sensor for measuring menstrual volume. We used the survey method and quantitative experiment-based methodology, which require data collection, analysis of data, and building models on top of it. We described design methods, experiments, and data collection and analysis process and investigated the sensor parameters, such as spacing between the conductive thread, weight, and location of the fluid drop. We evaluated the sensor with saline liquid, intravenous, and menstrual blood, and created models to estimate the menstrual blood volume. Through this research, we make the following quantitative and qualitative contributions.

- Design of a novel sanitary napkin-based sensor design.
- Investigation of different sensor parameters such as proper spacing to detect the output, effect of orientation, and weight on the sensor.
- A model for prediction of intravenous blood volume from the output voltage created using

blood data of 18 participants.

- A model for the prediction of menstrual blood volume from the output voltage was created using 40 menstrual blood data collected from 10 participants.

3.1 Interviews with Healthcare Practitioners

To better understand the problem and the challenges, the important parameters of menstrual health-related issues, early symptoms and signs of it and how gynecologists detect it, we conducted semi-structured interviews with five doctors who are Gynecologists at different government health care centers.

The semi-structured interviews took around 45 min to 1 hour. We (Two researchers) took field notes of the interviews as the gynecologists did not agree to record the interview session. We stored the scanned copy of the note on the password-protected computer system. We used deductive thematic analysis [127] to identify the gynecological issues and symptoms and available methods to detect these. The codes were informed by previous literature and our research objectives. Examples of codes included “*women’s health issues*”, “*gynaecological problems*”, “*menstruation*”, and “*infertility*”. We conducted a semantical content analysis of the field notes with a focus on word frequency.

- *What are the most common gynecological issues?*
- *What are the symptoms of these diseases?*
- *How do you diagnose the problem?*
- *What are the available methods to monitor the symptoms of these issues?*
- *In India, how frequently do women visit gynecologists?*
- *At which stage of the disease do the women come to the gynecologists?*

Our discussion with gynecologists identified important factors to consider for a design. Two key symptoms of menstrual issues are irregular menstrual cycles and abnormal menstrual bleeding, such as heavy flow or scanty flow. The interview results also suggested that women in India visit gynecologists only when they are pregnant or face issues like infertility or miscarriage. One gynecologist said

I treated one patient who consulted me as she was not able to conceive a second baby, she has a very irregular cycle with sometimes six months not having a cycle. It was strange; she did not consult any gynecologist for that issue.

Only young age women 19-25 years visit gynecologists if they face problems like abnormal menstrual bleeding, bleeding colour change, etc. One gynecologist told

”College-going young females are more concern about their health, and we are getting more and more young females who care for their menstrual health and consult us if they see any abnormalities”

Regarding the methods of detecting the issues, gynecologists told us that the methods are subjective. Pictorial Bloodloss Assessment Chart (PBAC) [102] is the widely used method for estimating menstrual blood loss, which is inaccurate due to biases. Practitioners asked patients if the menstrual cycle is regular or not, menstrual cycle duration (number of days), frequency of sanitary napkin changes, number of total sanitary napkins used, and any other issues if the patient is facing like abnormal pain, bleeding after sex, headache, stress, etc.

Based on these details, we identified a lack of tools to estimate abnormal menstrual bleeding, Taboos, stigma, and shame associated with menstrual health problems are the biggest challenges to healthy menstruation and overall women well being. Combining these, we need a menstrual blood volume sensing system that can measure the blood volume, store and analyze data in a private setting and provide feedback to the users regarding menstrual health, as well as share it with the practitioners. Our contribution to this thesis is to build the sensor and test it on a benchtop setting with different types of body fluids. We also created the wearable sanitary napkin system to understand the effect of physical parameters and activities on the sensor with saline liquid.

We also asked 20 females aged 19-35 regarding their preferred sanitary product and brand. Eighteen out of 20 participants replied that they use a sanitary napkin to manage their menstruation. 2 use a menstrual cup and sanitary napkin interchangeably. 17 out of 20 participants preferred using Whisper napkin, which is a well know Proctor & Gamble product.

The following sections describe the design details of the sensor, methods of parameter testing, and evaluation of the sensor. Since no previous data is available to us on the designs, materials, or menstrual blood and the methods, processes, and challenges in working with sensitive, limited, intimate body materials, we described the design steps and procedures to support future research in this area with personal body materials and technology.

3.2 Sensor Design

We started our design with various design options such as putting conductive threads horizontally along the sanitary napkin, putting many vertical conductive threads on the napkin, etc. As these required stitching many threads throughout the napkin, it increased the time of stitching and cost as well. We wanted to cover the whole napkin area at a low cost and to create the sample for testing in less time. Therefore we created two conductive traces along the napkin; however, the spacing between the thread was selected from parameter testing methods described in the following sections.

The working principle of our sensor is based on the change of resistance of the fabric with the added volume of fluid. We designed this sensor especially for females to wear. We have used the low cost (\$0.043 per meter) conductive thread (resistance 2.7 ohm/foot, thickness 0.17 mm) to create the conductive tracing running parallel along the two sides of the sanitary napkin as shown in Figure 3.1(b). 2 feet long thread was used to create one conductive trace (resistance approx 5.4 ohms). Since this resistance is very small (order of 100 difference) compared to the fabric resistance we have ignored the effect of this in our calculations. The change in fabric resistance with the fluid volume is sensed as the output current change.

We have used the third layer of the popular and widely used brand of Whisper sanitary

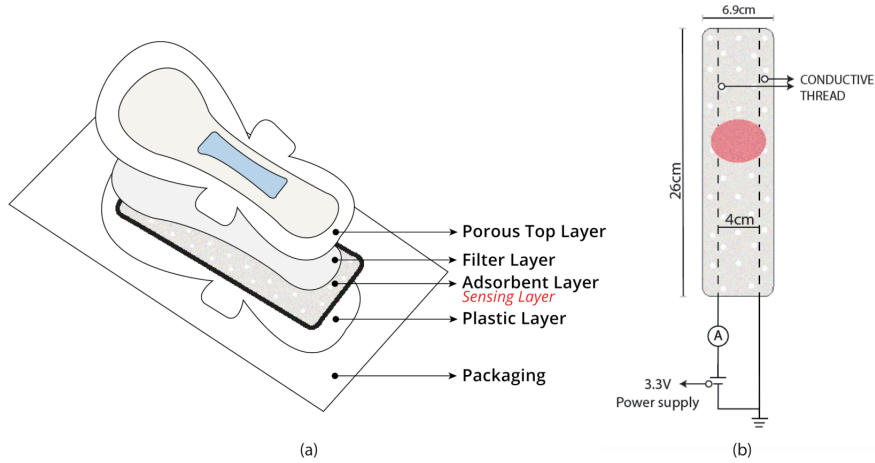


Figure 3.1: (a) Layers present in disposable sanitary napkin, (b) Circuit for parameter testing

napkins from Procter and Gamble health and hygiene for integration of our sensor. In addition to this, it is made by a machine-controlled process, so we can safely assume that the parameters of the fabric remain the same for the same size and same brand. It has four layers as shown in Figure 3.1(a) of which the bottom layer is used for packing the napkin that is to be removed before wearing. The top layer that directly touches the skin remains dry as it is a porous layer which allows the fluid to pass through. The second layer acts as the filter for the tissues of the menstrual blood, the third layer being the absorbent layer absorbs the blood, and the layer below it is an impermeable plastic layer to prevent the leakage.

Our sensor is passed through several bench-testing methods to investigate the effect of different parameters on it. Due to the limited availability of blood, we initially tested our setup with 5 mL of Normal Saline (0.9% NaCl). The saline liquid is readily available for use and it also has similar electrolyte properties to that of human body fluids such as sweat and urine. We have added 1mg of food colour to the saline liquid to differentiate the fluid from the sanitary napkin. We have chosen the 5 mL fluid because a regular-size sanitary napkin or tampon can absorb 5 mL of menstrual blood without leak^[1]. For all our parameter testing experiments we used an input voltage of 3.3 V at one conductive trace, and the measurement was taken after the 20s of dropping fluid, giving enough time to absorb the fluid sample into the sensor and also imitating the gradual and sporadic discharge noted by the survey participants. The current

¹<http://www.cemcor.ubc.ca/>

readings were taken from DMM4040A benchtop multimeter. This data can be transferred to a mobile device or cloud-based server in real time for processing.

3.3 Parameter Testing

The parameters investigated for the development of the sensor are:

- Space between the conductive traces
- Orientation
- Weight
- Location

These parameters have been tested with

- Saline liquid of different osmolarities and ions.
- Human blood of 18 participants
- Menstrual blood of 10 participants

3.3.1 Spaces Between Conductive Traces

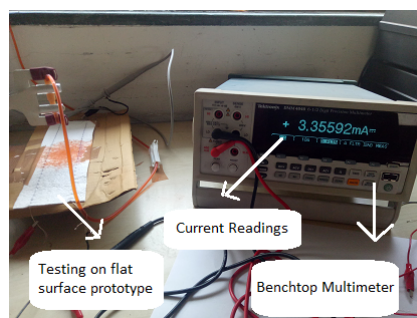


Figure 3.2: Experimental setup for Space testing

The goal of this experiment was to explore the optimum space needed between the conductive traces to detect a large range of blood volume starting with the minimum value of 0.5-1.5

mL of the absorbed liquid. This information helped us in identifying the trade-off between the sensing system's resolution and hardware requirements.

To conduct this experiment total 20 samples were created with conductive thread spacing of 1 cm, 2 cm, 3 cm and 4 cm (5 samples of each spacing) of size 26 cm X 6.9 cm and using the 3rd absorbent layer of Whisper sanitary napkin (refer to Figure 3.1(a)).

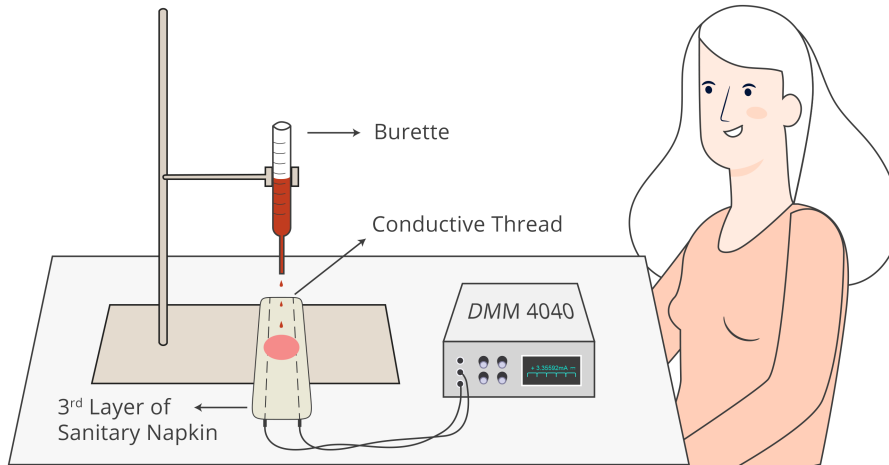


Figure 3.3: Schematic of the setup for space testing

We placed the sample at a fixed position on the flat surface of a burette stand, and the liquid was poured onto the centre of the napkin, drop by drop 0.5 mL at a time with a waiting time of 20s, using a saline drip from a height of 4 cm. Figure 3.2 shows the setup used for this experiment and its schematic is shown in Figure 3.3.

The spacing between the conductive traces was characterized by the minimum volume of fluid it can detect and the linear increase in current with the volume of fluid added. 1 cm, 2 cm and 3 cm spacing can detect 0.04 mL, 0.1 mL & 0.2 mL of fluid respectively. The detection event was noted as soon as the current changes, however, this change was quite small to be detected and the volume difference of 0.1 mL would not make any significant difference to the fluid volume prediction which is even more insignificant while testing with menstrual blood because menstrual blood property changes inherently with the participant which in turn affect the absorption, thereby the resistance of the sensor. Therefore, we finalized 0.5 mL fluid as the minimum resolution and 4 cm spacing for our circuit. Figure 3.4 shows that the output current

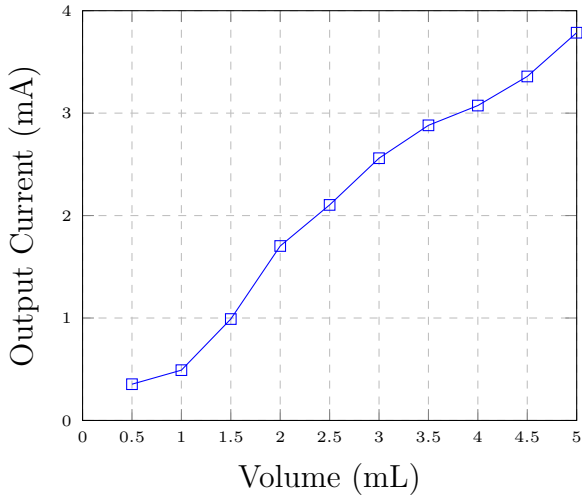


Figure 3.4: Output Current change with the added volume of Normal Saline

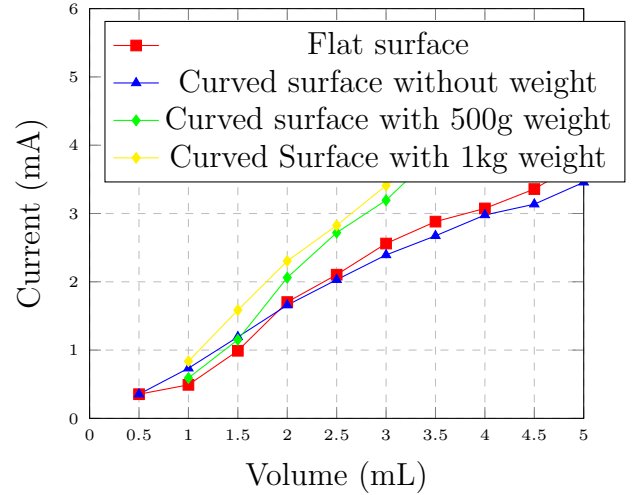


Figure 3.5: Comparison of currents on curved surface, applied weight on sensor with flat surface without weight

increases linearly with the volume. As explained earlier, this experiment was done keeping the napkin on a flat surface, however, a more practical scenario would be to experiment with the sensor keeping it on a curved surface, similar to the placement on the body. Our next experiment investigates the effect of the curved surface on the spreading and absorption of fluid.

3.3.2 Orientation

As the practical situation consists of the change in body position and hence the angle of the attached sanitary napkin, this test explores the effect of this change in the orientation of the napkin on the sensor readings.

We prepared five samples with 4 cm spacing between conductive traces. A prototype of the curved surface was designed as shown in Figure 3.7(a) by body fitting a corrugated sheet on the lower body of a woman of height 5 feet 4 inches and body weight 56 kg. Henceforth this prototype is used in all our subsequent experiments. The output current is measured using Agilent DMM 4040A.

A Sanitary napkin was placed inside the curved surface, and 0.5 mL of fluid was dropped at the centre from the saline drip. The fluid drop location was shifted to 1 inch from the centre to

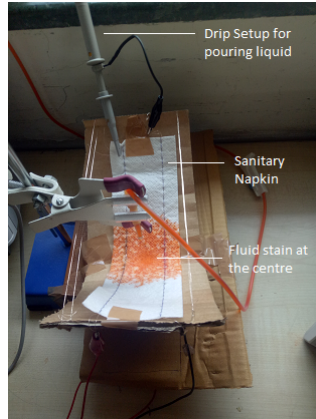


Figure 3.6: Setup in use

account for the fact that fluid drop is not perpendicular on the napkin whenever women wear it, as shown in Figure 3.7(b). The experimental setup is shown in Figure 3.6 for this experiment showing the angle change.

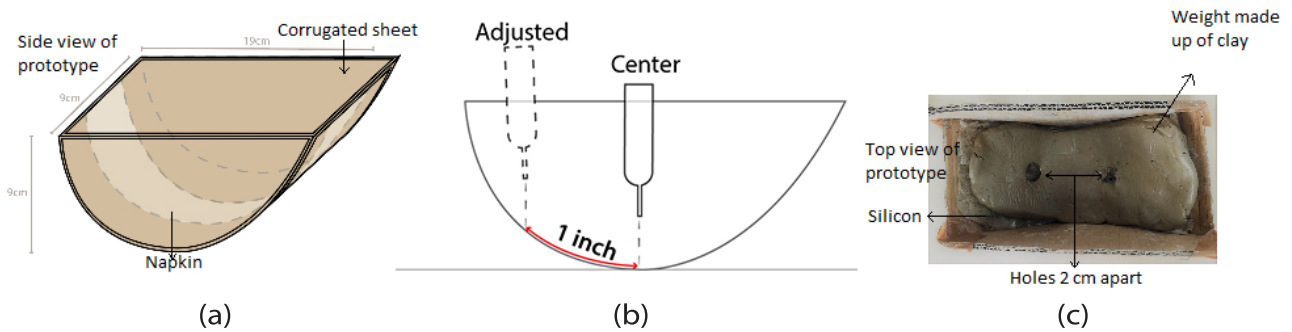


Figure 3.7: (a) Prototype, (b) Fluid dropped location for orientation change, (c) Final prototype with weight

The curved surface does not have much effect on the fluid spread, and we observe a similar linear increasing trend of current as in the flat case as shown in Figure 3.5.

3.3.3 Weight

During the use of a sanitary napkin attached to an undergarment, pressure is applied on it from the elastic material of the garment as well as the body weight. Note that we do not consider the lateral pressure applied from thigh muscles. The goal of this experiment is to determine how sensor performance changes with the change in weight applied to the sanitary napkin. We tried to simulate the practical situation of the on-body condition by varying the pressure applied on

a sanitary napkin in turn, by changing the weight of the napkin. The pressure applied to the napkin would depend on the women's body weight, that varies considerably depending on the activity and posture. The best method of testing would be by putting it on physically, which requires complex analysis and computation. However, by following Foo et al. [78] paper, we have experimented with 500g and 1kg weight.

We prepared 10 samples with the third layer of Whisper XL⁺ and tested half of the samples by placing 500g & 1 kg weight, respectively. The weights were made using clay and were spread evenly on the napkin. A silicon sheet (created by GP 1000 silicon) was placed in between to match human skin-like properties. A complete setup with clay and sanitary napkin is shown in Figure 3.7(c).

We dropped 0.5 ml fluid, using the drip tube attached to the saline bottle at a time through the hole at the centre of the clay, and the output current values were recorded after 20s.

We observed from the results shown in Figure 3.5, that with the increase in applied pressure, fluid was quickly absorbed by the napkin in the vertical direction at the cost of reduced horizontal spread and hence it took a little longer to connect the circuit. Therefore, instead of 0.5 mL, we started getting data from 1 mL. Also, we noticed that there was not any significant change in output current with the change in weight (500g & 1 kg). Henceforth, in all our further experiments, we have considered 500g weight only.

3.3.4 Fluid Dropping Location

Women have an active lifestyle with various activities such as walking, sitting, standing, etc. To examine the dropping of fluid at different locations while the user sits, sleeps (refer Figure 3.8, 3.9), we have simulated the sitting and sleeping position of the individual by dropping the different proportion of fluid at two locations, centre and back end of the napkin respectively. Though in real use, more intermediate states will occur as well as body contours will lead to the dispersion of blood on a larger surface, we find these two condition states to be a good approximation.

Through this experiment, we have tried to investigate if our volume sensor can detect the

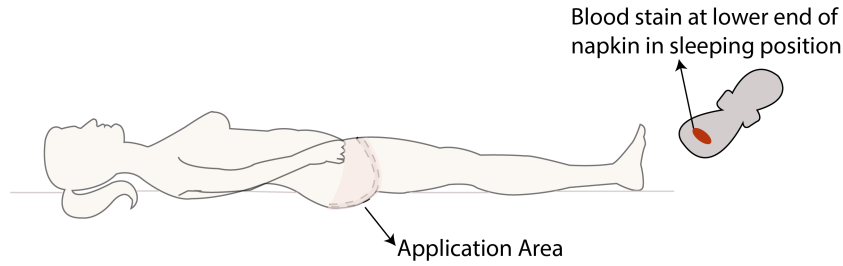


Figure 3.8: Location of stain at sleeping position

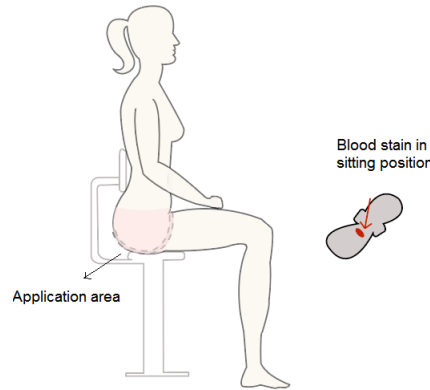


Figure 3.9: Location of stain at sitting position

amount of fluid correctly if the fluid was dropped at multiple locations on the sensor and not accumulated in a single location.

We prepared 5 samples with 4 cm space between conductive traces using Whisper sanitary napkin’s 3rd layer. The clay model created for weight has two holes to drop fluid through it (refer Figure 3.7(c)). The distance between the two holes has been selected based on observations of 5 used sanitary napkins collected from participants with activity as sitting, standing and sleeping. We gave Whisper XL⁺ with a package where participants filled in the information about the start time, the end time of using the napkin and the activity. After collecting the napkin, we measured the location of the stains and spread them on the napkin. This led us to decide the location of the hole created for this test, as one at the centre and the other at the back end, at a distance of 2 inches from the center.

A silicon layer was placed in between the sanitary napkin and clay model for simulating human skin-like properties. The sanitary napkin was placed inside the curved surface.

We did two experiments with two different proportions of fluid at two locations. To recreate

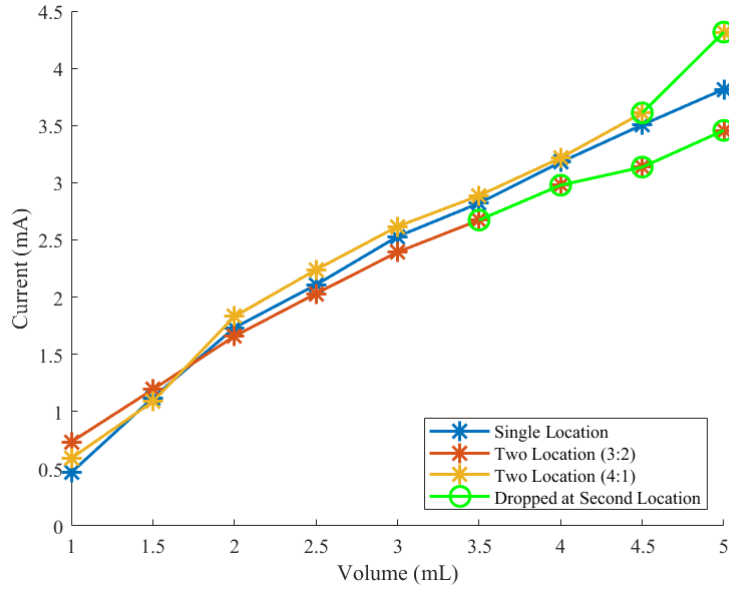


Figure 3.10: Comparison of currents with 3:2 and 4:1 proportion of fluid dropped at different location the real-life scenario where the maximum stain is nearer to the center we have used the ratio of 3:2 and 4:1 between the center and off-center location.

The fluid was first dropped at the center, then at the back (refer to Figure 3.11). At the time of dropping fluid at the center, the curved model was kept in an upright position while it was slanted backwards when dropping at the back so that the pressure was applied accordingly.

The result in Figure 3.10 shows that the liquid volume can be identified with a different amount of fluid if dropped at a different location. The *single location* denotes the current

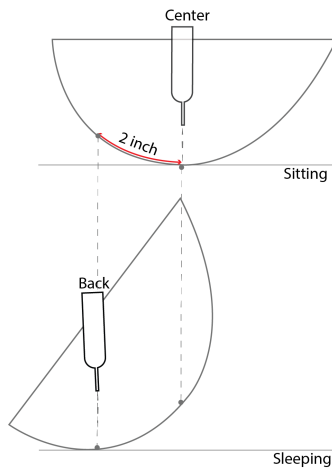


Figure 3.11: Fluid dropped location for different locations with upright and slanted positions

change when 5 mL fluid is dropped at the center. The *two location* (3:2) and *two location* (4:1) shows the current change when 3/4 mL fluid is dropped at the center (center hole) and the remaining 2/1 mL fluid is dropped at the back (back hole) of the clay model, as shown in Figure 3.7(c) respectively. From this experiment, we can conclude that adding fluid at a different location would decrease the resistance of the fabric and when the fluid merge between these *two locations*, they act as parallel resistance. This helped us to measure the fluid volume correctly even if the drop is at a different location.

3.4 Testing With Other Saline solutions

The initial experiments we conducted for parameter investigation were using normal saline (0.9% NaCl Osmolarity 308 mOs per liter). We also tested with two other known saline solutions- Lactated Ringer (Osmolarity 280 mOs per litre with Ca^+ , K^+ , HCO_3^-) and 1/2Normal Saline (Osmolarity 154 mOs per litre) to cover the blood Osmolarity range (which is 275-295 mOs per litre) and to see the effect of other ions on our sensor.

The experimental setup remains the same except 5.5 kOhm resistance is added at the output to create a voltage divider circuit as shown in Figure 3.14(b). Total 10 samples were tested with the lactated ringer and 1/2 normal saline. The voltage reading from the analog input pin is measured and stored along with the added fluid volume. The sensor was placed inside the curved surface with 500g weight applied to it. Figure 3.14 shows the complete circuit with a microcontroller and the sensor.

The fluid was dropped at the center of the napkin (considering sitting position) through the hole created in the clay weight and silicon layer. After dropping 0.5 mL of the fluid and waiting for 20s, the output voltage is measured and data was collected using a microcontroller and serial interface open on a connected laptop.

Figure 3.12 shows the output voltage change with the volume change of three different saline liquids: NS (Normal Saline), 1/2 NS (Half-normal saline), and LR (Lactate Ringer). From the graph, we can conclude that the increasing trend of the voltages with added volume is the same

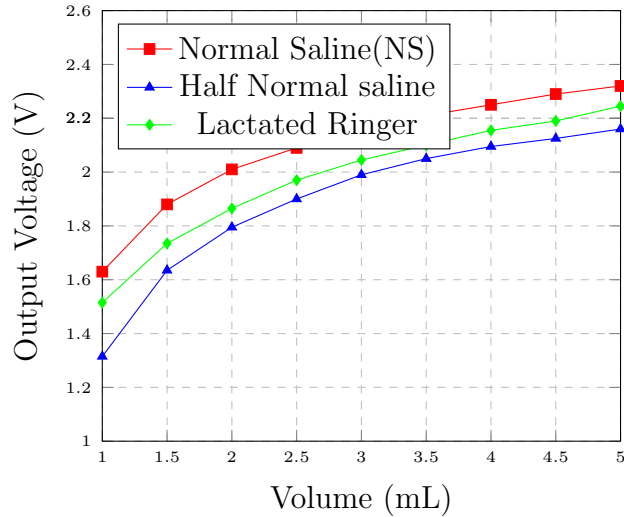


Figure 3.12: Comparison of output voltage with the volume of fluid dropped

for these liquids. The change in output voltage values is due to the different osmolarities of the fluid. This also confirms that the presence of these ions in blood will not change the trend line of our graph. We can also observe that the higher osmolarity fluid has higher conductivity.

3.5 Testing With Intravenous Blood

In contrast to experiments with saline solutions, it is much more challenging to conduct tests using human blood samples. Unlike saline solutions, human blood is a non-Newtonian fluid whose viscosity changes under pressure thus adversely affecting its flow and absorption in a sanitary napkin. Moreover, its viscosity also changes with time due to coagulation. Furthermore, while saline liquids are cheap and easy to acquire from the market, human blood is not as easy to acquire and store. Despite these challenges, we managed to collect intravenous blood samples from 25 participants out of which we could only use 18 for our evaluation.

We prepared 18 samples with 4 cm spacing between two conductive threads using Whisper XL⁺ sanitary napkin. As our final circuit has to be integrated into the full napkin, we have added all the layers of the sanitary napkin (refer Figure 3.14) in our final human blood testing setup. Each sample was placed on the curved model and data was collected using microcontroller nRF52832.

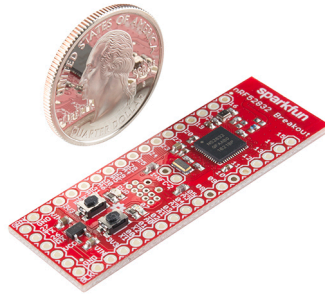


Figure 3.13: nRF52832 SparkFun Breakout Board Microcontroller

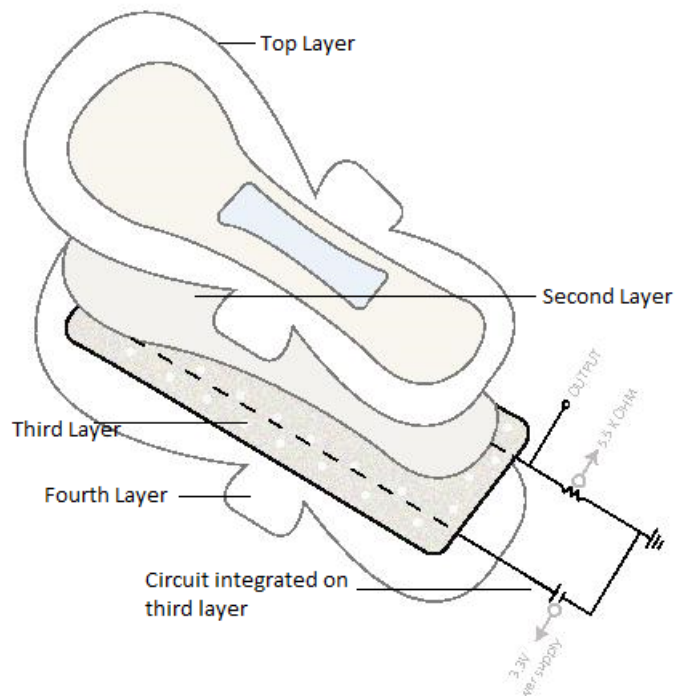


Figure 3.14: Sensor circuit integrated into the napkin

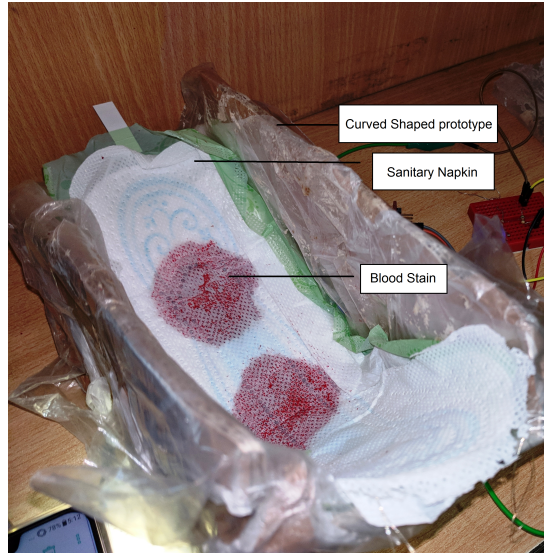


Figure 3.15: Intravenous Blood sample

Getting IRB approval for conducting a study with human blood was challenging, especially in an engineering research Institute like us. As this was an invasive process, IRB questioned us on the measures we took to ensure the safety of users, avoid the risk of infections etc. We addressed the concerns by highlighting the fact that we took the help of the doctor and the nurse who were regularly available and the gynaecologist who visited our institute once a week. For example, the medical practitioners helped us with details of the experiments, such as drawing blood etc.

After getting the approval from institute IRB for our study, we recruited 25 female participants of the age group between 20-35 (mean age 26 years) from our institute using snowball sampling. Each sample was tested while placing it inside the curved surface. To create a data set with female intravenous blood for this sensor we conducted this study at our institute's infirmary, where a medical practitioner drew 5 mL of blood from the participants. We dropped 5 mL of blood in 0.5 mL parts at the center of the napkin and waited for 20 seconds before taking readings. The experiment was completed within 8 minutes to avoid coagulation that onsets as soon as exposed to air and becomes a serious issue after 8 minutes. We did not add anticoagulants to preserve the natural properties of the blood. Figure [3.15](#) shows the experimental setup in use while conducting the tests using the blood.

We observed that the intravenous blood follows the same trend as the saline liquid, i.e. the

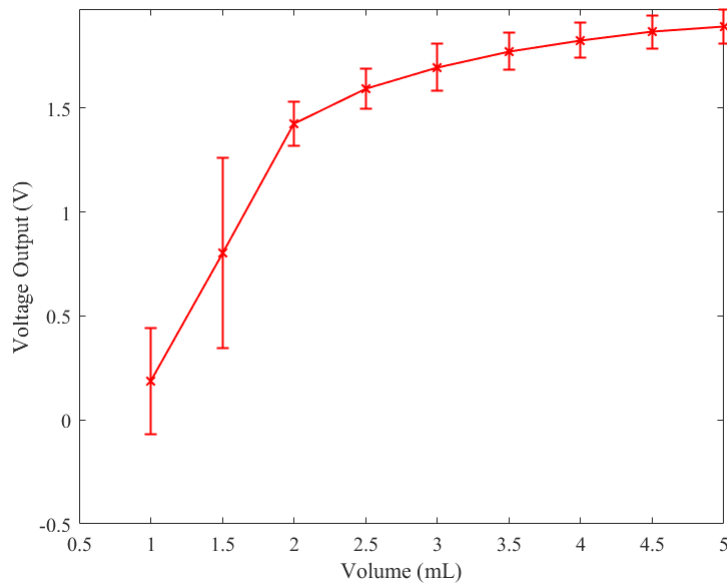


Figure 3.16: Standard deviation of Blood samples

output voltage increases with the increase in fluid volume. Figure 3.16(b) shows the average output voltage variation with the volume of 18 participants. The error bar shows the standard deviation of the output voltage. During the experiment, we noticed that the blood viscosity changes with applied pressure, therefore, the absorption of the blood changes; as a result, we got the readings from 2 mL for 12 participants instead of 0.5 mL which were the case for saline liquids. From the figure we can see that the standard deviation is more at lower volume values; this was due to the circuit did not get connected at 1 and 1.5 mL of fluid drop for many participants. In case two location experiment also the circuit did not show any voltage difference until the circuit gets connected.

3.6 Testing With Menstrual Blood

The primary objective of this sensor design activity is to measure the menstrual blood loss volume during a menstrual cycle which can be important for proactive monitoring of menstrual health of women. However, evaluating our proposed sensor using menstrual blood is difficult for the following reasons. First, while intravenous blood was challenging due to its non-linear viscosity, the menstrual blood has additional challenges due to the variable composition. The

second challenge is getting a sufficient number of menstrual blood samples as it is available only once in a month per participant. Lastly, even if we could find enough participants, most of the women use a sanitary napkin during a period which does not allow for any testing as the blood gets absorbed into the napkin which is then discarded. But for evaluating our sensor we need it in a fluid form.

To allow for the collection of menstrual blood samples in a liquid form, we relied on the use of a menstrual cup. A menstrual cup (refer Figure [3.17](#)) is a reusable feminine hygiene product made of soft medical grade silicone which is inserted into the vagina to collect the menstrual blood during the menstrual cycle. However, we discovered perceived social, psychological and physical barriers due to which women are not ready to use a menstrual cup. These challenges include the misconception of losing virginity from hymen breakage, fear and inconvenience of inserting the cup into the vagina, silicone allergy and perceived difficulty of using a menstrual cup with Intrauterine Devices (IUD).

To find enough participants for our IRB-approved study who would be ready to use the menstrual cup, we conducted multiple awareness sessions on the menstrual cup usage and data collection process in our Institute under the supervision of a medical practitioner who answered all queries. We targeted more than 40 people of different regional and professional backgrounds such as housekeeping staff, students, researchers, and faculty for data collection. We noted the expected menstrual cycle date of those who agreed to give us menstrual blood samples and provided them with a free menstrual cup and a container, a day before their expected date. Despite these efforts, we observed only a minor change in the perspective of women toward the acceptance of a menstrual cup as a sanitary product. Eventually, 10 participants agreed to provide their menstrual blood samples collected using menstrual cups. But the fact remains that women find a sanitary napkin to be more socially acceptable and easy to use (perhaps due to its familiarity) sanitary product than a menstrual cup. Hence we continued with the sanitary napkin-based sensor design.

A sample of menstrual blood is available once a month from each participant. So, we collected the phone numbers and expected menstrual cycle start dates from the participants

who agreed to participate and signed the consent form. We also share our numbers with them so that they can inform us if menstruation started early. We called the participants two days before their start date, provided the menstrual cup, and demonstrated how to use it through videos. We also provided them 30 mL labeled specimen container and asked the participants to put the day and time on the container when they took the sample. Participants called us when they collected the sample, and we collected the container from them. We collected the samples from the females of our institute to minimize the delay between sample collection and data collection after the experiment. After performing the experiments and collecting data, we disposed of the container, sanitary napkin, syringe that we used to draw the blood, gloves, mask, etc. We also sanitized every electronic equipment and other device we might have touched during the experiment using disinfectant wipes and sprays.

We conducted a four-month-long study wherein we collected 40 menstrual blood samples from 10 participants in total. We got a maximum of two samples per day (6-7 hours apart) during the initial two days of the menstrual cycle. The minimum and maximum volume of samples collected was 1 mL and 15 mL respectively. Consequently, we were able to conduct the following experiments required to evaluate our sensor.



Figure 3.17: Menstrual Cup with markings on it

The experimental setup was the same as the human intravenous blood setup except while calibrating the spacing between the conductive thread from 4 cm (previous) to 3 cm (proposed). We observed a minimum detection change from 1 to 1.5 mL with human blood to 2-2.5 mL with menstrual blood in 4 cm. We tested this with two samples of 4 cm and 3 cm each with two menstrual blood data collected from 2 participants. After the adjustment to 3 cm, the minimum detection level became 1-1.5 mL for menstrual blood. So we have used 3 cm spacing

for further experiments.

With the activity or movement of the women, it is very unlikely that all the menstrual blood will drop at a single location only, it will either spread out on the pad or will drop at multiple locations. If it is dropped at a single location only then it might start leaking and the woman would change the napkin. The best-suited scenario of dropping blood on the napkin can only be determined during the in-the-wild study which is beyond the scope of this thesis. Therefore, in this thesis, in the design of our experiments with menstrual blood, we tried to simulate all the possible scenarios of blood dropping at one location, multiple locations, and multiple locations with large volumes.

3.6.1 Testing On One Location

The goal of this test is to observe the sensor performance with maximum volume content at one location.

We measured 0.5 mL of menstrual blood and poured it on one location at once and waited for 40 seconds before capturing the data so that it gets absorbed in the napkin, as it was highly viscous due to the presence of endometrial tissues and vaginal fluids. We have used samples with a maximum of 8 mL volume for this experiment. We conducted this test with thirty-one menstrual blood samples collected from 10 participants.

The goal of this experiment is to verify that our sensor is able to detect the volume correctly when fluid dropped either at one location or multiple locations.

The process of dropping liquid is similar to the previous one, except for the change in volume and dropping location which is 3 mL at the center and 2 mL at a distance of 2 inches from the center point of the sanitary napkin. For this experiment, we chose those samples which were of volume more than 10 mL and performed two experiments (same location and on different locations, each with 5 mL). The idea behind this is to make sure that the properties will remain the same for both experiments, as this might get changed for a different day or sample. We repeated this experiment with five menstrual blood samples collected from three participants.

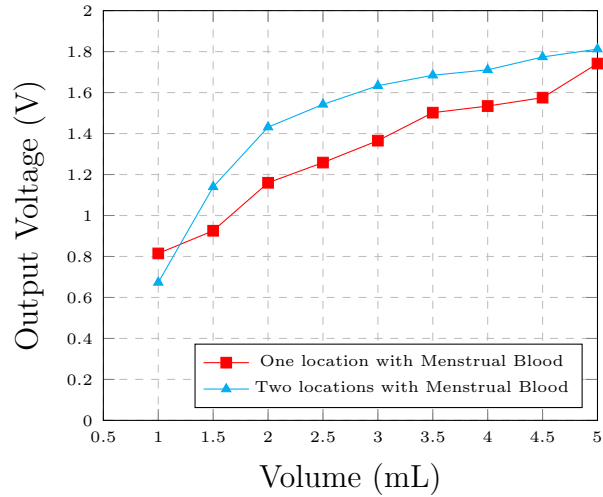


Figure 3.18: Comparison of average output voltages of one location experiments with two location experiments using Menstrual Blood

3.6.2 Testing With Large Volume

Our goal is to see if our sensor will be able to respond to large volumes (up to 12 mL volume). This experiment was designed to observe the practical scenario of heavy menstrual flow at multiple locations where the menstrual blood is spread out on the napkin. Menstrual blood loss volume of more than 80 mL in one cycle (4-5 days) is considered a heavy flow. Thus, in 12 hours which is the clinically advised time to change the Whisper XL⁺ sanitary napkin, above 10 mL would be the calculated heavy flow. Therefore, we have used 12 mL as the large volume for this experiment.

We are considering 12 mL as a large volume. We poured 0.5 mL of blood, each time till 8 mL at the center of the napkin and the remaining blood at multiple locations of the napkin. We repeated this experiment with three menstrual blood samples collected from two participants.

We observed a similar trend of the results (refer Figure 3.19) of one location experiment with intravenous blood and menstrual blood. The initial values of intravenous blood data started from a lower voltage as the intravenous blood data was collected with 4 cm samples where the initial connection of the circuit started from 1.5 to 2 mL and the resistance was higher. We saw an increasing trend in the large-volume experiment which clearly reflects that our sensor works for volumes greater than 5 mL. The large volume curve becomes saturated around 7.5-8 mL

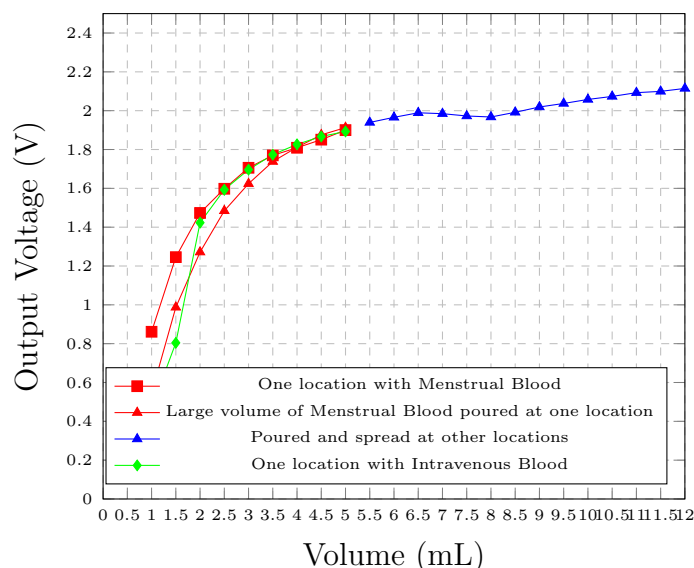


Figure 3.19: Comparison of output voltages of one location with Menstrual Blood, one location with Intravenous Blood, large volume with Menstrual Blood

because of pouring a large volume of more than 5-6 mL at one place will completely saturate the area and it starts leaking. The onset of saturation and leakage depends on the menstrual blood volume and viscosity. When the viscosity was higher with more endometrial tissue the saturation happens near 8 mL whereas with less viscous blood it gets absorbed easily and saturates the area with 5.5-6 mL of blood. The blood absorption capacity of various sanitary napkins has been assessed in paper [128] showing Whisper XL+ napkin's blood absorption capability at one location is approximately 6-8 mL before it starts leaking from the lateral rim which is confirmed by our experiment results.

The blood drop location changes with the daily activity of the women and the sanitary napkin should be changed after 6-8 hours of use, therefore our sensor will be able to detect the volume of blood collected if it is more than 5 mL till 12 mL as tested.

Figure 3.18 shows the average output voltage changes of menstrual blood experiments on one location and two locations. We observed that although we use a single sample for these two experiments from one participant, the output voltage differs for these experiments. The reason for this was the content of tissue varies in samples used for each experiment which changes the density of the blood. We verified this by dividing the same sample into two 5 mL volumes which showed a weight difference of 0.77g.

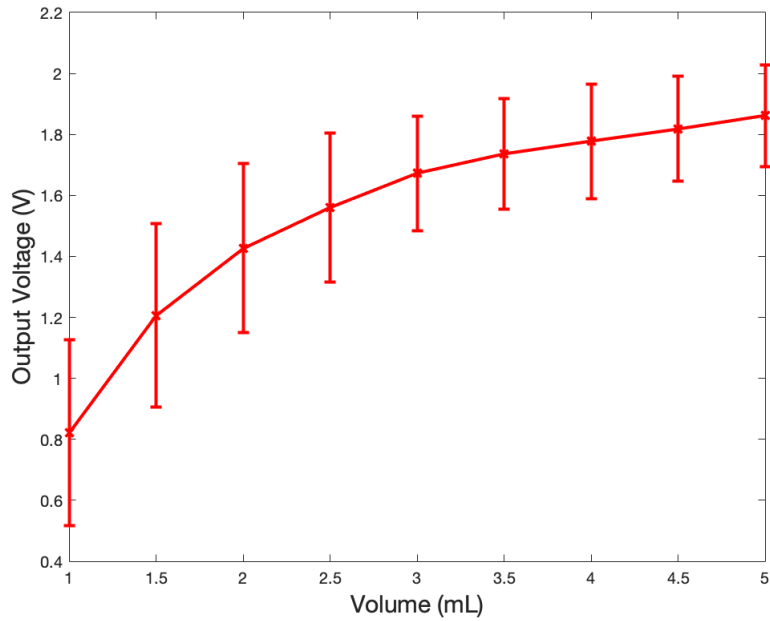


Figure 3.20: Standard deviation of Menstrual Blood samples

Figure [3.20](#) shows the average output voltage variation with the menstrual blood volume. The error bar shows the standard deviation of the output voltage. From the figure we can see that the standard deviation is slightly higher at lower volume values, this was because of the variation in absorption at a lower volume of fluid for some participants.

Even after the spacing adjustment, the volume of blood loss can remain undetected if the volume of the blood does not connect the circuit which happens when the blood drop location changes every time. However, this is very unlikely as the sanitary napkin does not move much with respect to the user, except when the user changes activity.

3.7 Prediction Model For Intravenous Blood

Our experiments were controlled experiments where we have the known volume of fluid, and we measured the change in output voltage. However, we want to detect the volume of the absorbed blood in the sanitary napkin from the voltage. To do that we have built a model which can predict the volume from the voltage reading.

We have collected data of output voltage change with the added volume. The output voltage

data readings are from volume 1 mL to 5 mL. We gather data 20s after dropping 0.5 mL of blood and gather data for 10s thus logging multiple values for each step which we later averaged out for each of 18 participants. The data were logged using the serial interface at the baud rate of 9600. We averaged each volume of data collected for every participant. Therefore, we gather 9 volume data for each participant for 1-5 mL fluid. In total, we had 162 data points.

We used machine learning to analyze the data and construct a prediction model to predict the volume of the fluid using the voltage output. We used the Machine Learning Regression Learner application of MATLAB to construct different models. Using this application we were able to fit the data using multiple modeling techniques such as SVM, Trees, Linear Regression, and Gaussian Regression. We used user-independent testing to divide our dataset into training and testing data sets with a ratio of 8:2. We split the data based on participants in order to reduce bias towards a single participant while training a model which may happen if we split the data based on different data points.

For the training dataset, the fluid volume was taken as the response variable (label) and voltage output as the predictor variable (feature). We then trained different models on our data and selected the ones with the least Root Mean Square Error (RMSE). The RMSE is a frequently used measure of the differences between values (sample and population values) predicted by a model and the values actually observed. The lower the value for RMSE the better the model is for predicting. But this has a drawback in the case when the algorithm starts overfitting the data in the model.

In order to reduce the overfitting we took four models with low RMSE values namely SVM (Fine Gaussian), Tree (Fine Tree), Gaussian Process Regression (Mattern 5/2), and Gaussian Process Regression Exponential. We then performed bootstrapping with all models 1000 times in order to calculate the error in the predictions with the ground truth values. Bootstrapping falls in the broader class of re-sampling methods. It relies on random sampling with replacement to allow us to assign the measure of accuracy to sample estimates. For our dataset, we calculated the residual errors for the different models. Residual Error is the absolute difference between the predicted values and the ground truth values. We then compared them to decide the model

with the best fit for our data. The box plots for the 5 models can be seen in Figure 3.21(a). The box plots are the standardized way of displaying the distribution of data based on the five-number summary: minimum, first quartile, median, third quartile, and maximum. For comparison we took the median values into consideration, the model with the lowest median would be the best fit for our model as it will be the one with the least errors for maximum cases. From Figure 3.21, we can conclude that SVM Fine Gaussian is the best fit for our data as it has the lowest median value.

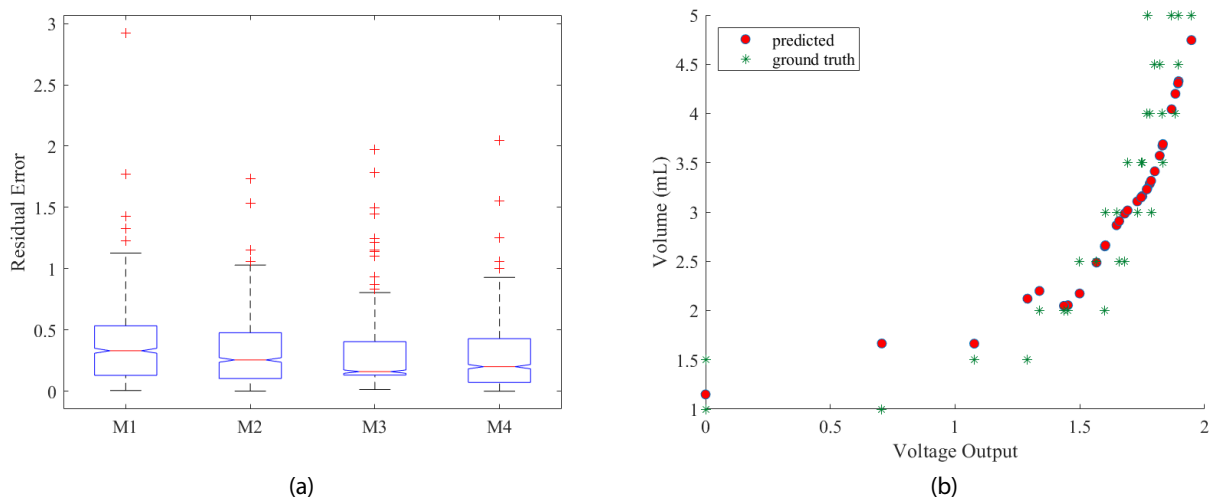


Figure 3.21: (a) Intravenous Blood Boxplots for Models M1:Gaussian Process Regression (Mattern 5/2) M2:Gaussian Process Regression Exponential M3:SVM (Fine Gaussian) M4:Tree (Fine Tree), (b) Predicted volume and Ground Truth Value after testing on SVM Fine Gaussian Model

After selecting the model SVM Fine Gaussian we performed testing on it using the test data set. The Mean Absolute Percentage Error (MAPE) [129] was calculated in order to determine the accuracy of the model. After running the test multiple times on multiple test data sets the MAPE was calculated in the range of 11-15% for the SVM Fine Gaussian Model. We also plotted the predicted values and the ground truth values which can be seen in Figure 3.21(b) showing us the final curve for our model. The error for predicted values ranges from 0.01-0.45 mL. The maximum error is seen in the starting volume values ie. 1-1.5 mL. This is due to biasing of the model towards the participants who's circuits got connected in the initial stages ie. at 1 mL instead of 1.5 mL. We have created our model based on user-independent testing

which is bound to give us lower results because of the inherent variation of blood composition of participants' samples. We hypothesize that user-dependent testing will lead to a better result. But it requires the collection of larger amounts of data from a single participant which was not feasible.

3.7.1 Prediction Model For Menstrual Blood

In order to predict the volume of menstrual blood being collected in the sensor, we proceeded in the same manner as intravenous blood and built a prediction model.

We collected the data in a similar manner as intravenous blood, by keeping track of the output voltage change with the change in the volume of menstrual blood. As menstrual blood is more viscous it took more time to get absorbed in the sensor, thus we increased the time gap between every reading of data from the 20s to 40s. We recorded the output voltage values for 10s and averaged them out to get data for every change in the volume of a participant. The data was logged for the complete volume collected for each participant.

We collected 40 menstrual blood samples in total, out of which we have used four samples for spacing experiments, 5 samples for two locations experiments. From the remaining 31 samples, we used 25 samples for the prediction model and we had to discard 6 samples as the volume of blood collected was below 5 mL. To create the model we used only volume till 5 mL thus giving us 9 volume data points per participant and 225 volume data points in total.

We followed the same procedure as intravenous blood to select the best model fit for menstrual blood. We first used user-independent testing to divide our dataset with a ratio of 8:2 into testing and training datasets. We then trained several models on the training dataset and used the ones with the lowest RMSE value for further process. To reduce overfitting, we followed the same procedure and took four models with the lowest RMSE values namely: SVM (Fine Gaussian), Tree (Fine Tree), Gaussian Process Regression (Mattern 5/2) and Gaussian Process Regression Exponential, and perform 1000 times bootstrapping on them. Then the models were compared using boxplots to get the best fit for our data. From Figure 3.22(a) we can observe that SVM Fine Gaussian is the best fit for our data as it has the lowest median

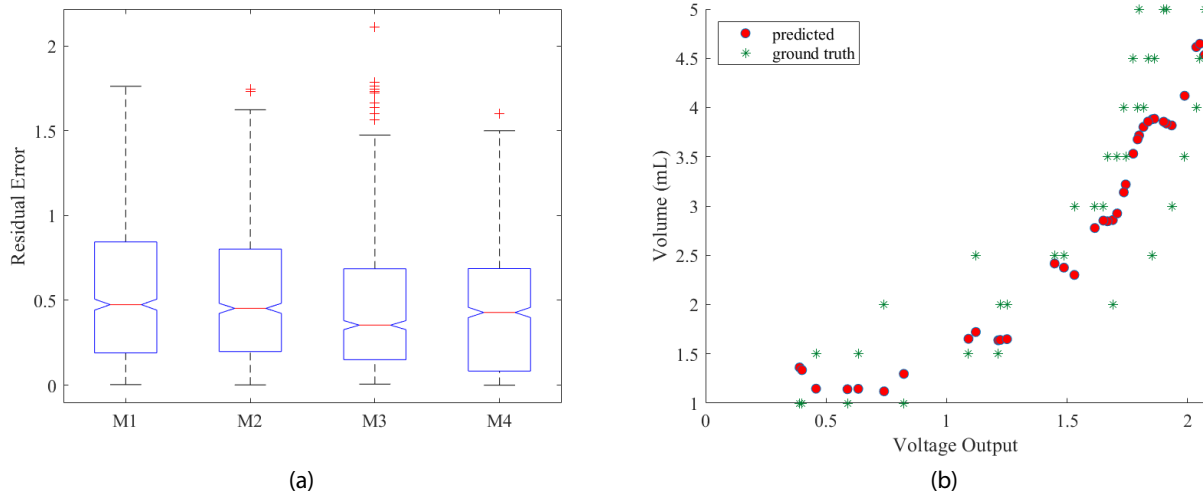


Figure 3.22: (a) Menstrual Blood Boxplots for Models M1:Gaussian Process Regression (Matern 5/2) M2:Gaussian Process Regression Exponential M3:SVM (Fine Gaussian) M4:Tree (Fine Tree), (b) Predicted Volume of Menstrual Blood and Ground Truth Values after testing on SVM Fine Gaussian Model

value.

MAPE was calculated in a similar fashion as intravenous blood, to determine the accuracy of the model. By testing using the test dataset on the SVM Fine Gaussian model, we calculated that MAPE was in the range of 15-30%. The error in predicted values ranges from 0.05-0.7 mL. The final curve for our model is shown in Figure 3.22(b). As there was overlapping for output voltage after 3 mL of menstrual blood, we saw an increase in error towards higher blood volumes. Also, the error observed in the menstrual blood model was more because of the inherent variations of the menstrual blood. The variations being: each user has different compositions for menstrual blood and each day in a single cycle with different content of tissues depending on the discharge and activity of the user. All of these properties also vary with every cycle thus leading to further variations. Moreover, we have done user-independent testing which is bound to give lower results because of inherent variation on user data.

3.8 Discussions

The work in this chapter was the first of its kind in the female health monitoring devices domain. With no baseline data availability, we had to overcome various roadblocks while conducting this research. Starting from building the research team and study, we faced multiple challenges related to methods to use, insufficient infrastructure, participant recruitment, sample collection, etc. In this section, we discussed them in detail to set the stage for future researchers working in personal care technologies and female health.

Experimentation with menstrual blood required handling this intimate body material, and participant gathering and investigation needed a motivated research team. Since this is a gendered body material, we asked female researchers. However, many refused to work due to safety and privacy concerns.

Since we are the first to work with sanitary napkin-based sensors, we adapted the iterative design method, keeping the users' safety and comfort in mind. None of the participants had ever worn something like this before, and that too in an intimate area, so clearly, there were concerns regarding the possibility of getting a shock. We had to address it while designing the sensor; we kept the current value far less than the safe current limit of the human body. We used conductive threads for users' comfort. Handling intimate body materials may spread and cause infections, so we took every possible safety measure. The complete testing was done in a separate room, wearing gloves and masks. We sanitized all the instruments after use and used disposable materials as much as possible. After the experiment, we disposed of each napkin in a disposable bag.

We intended to approximate the real-life scenarios as much as possible while conducting the experiments. We had the choice to either use real blood and simulate the situations or to use simulated blood or collect blood from the blood bank for conducting the experiments. However, we did not opt for these simulated blood methods to match the real fluid property of intravenous and menstrual blood. Furthermore, with the days of menstruation, the blood property changes for each person. There is an interpersonal variation of menstrual fluid as

well. Dropping the menstrual fluid on the napkin was difficult, with varying tissues in the blood, so we chose a syringe without a needle for drawing the blood from the container. The blood property remains the same for simulated blood, and it would be easy to conduct the experiments. However, it would not match the real scenario, and the models generated from these fluids would not match the true values.

The Wet Lab infrastructure was required to conduct this kind of research with biological fluid where the environment is controlled and safety and privacy are maintained. However, finding a private room without a glass window at the door in an engineering institute was challenging. We had to cover the door with a black sheet to make it a private room. Moreover, there were no proper facilities such as air conditioning to maintain the specific room temperature and humidity. We had to create our laboratory by adding all these facilities.

The recruitment of the participant was the biggest challenge in this kind of study with personal body materials. To find volunteers, we conducted multiple sessions to explain the motivation of our research, the data collection process, and other details regarding the technology. At the end of the session, we asked for voluntary participation in this study. Thirty female participants out of 40 we reached out showed interest in taking part, and we collected their menstrual cycle date and contact information. However, when contacted for data collection, twenty avoided the study for various reasons. Five participants also left the investigation in between for their other commitments. We also observed that some participants contacted us on their own after getting information from their peers and understanding that the menstrual cup was easy and convenient to use. Since we provided the free menstrual cup, it attracted the younger generation to participate.

The sample collection for intravenous and menstrual blood was challenging due to the uncertainty of the available sample and preparedness for the experiment. The medical practitioner of our institute collected the intravenous blood; the collection was difficult for some participants as blood was not coming out quickly. Therefore doctor had to prick two-three times at different places. For 5 participants, the blood volume was less than 5 mL which was our required volume. We also observed that blood property also changes from person to person. For some

participants, it was thin, and for others, it was thick and clotted easily. Though we designed our experiment to take less than 8 min (blood clotting time), in the case of 3 experiments, we found that blood started clotting before we finished the experiment.

Moreover, for menstrual blood, the amount of the fluid collected was uncertain, so we had to modify or cancel some experiments after collecting the sample. For example, for large-volume experiments with menstrual blood, we required a fluid volume of more than 10 mL from a person; however, we had to modify the investigation to a menstrual experiment with 5 ml if the volume was insufficient.

Additionally, first-time users of menstrual cups provided for sample collection sought our help in using and handling them. They faced challenges like leaking and staining the clothes for improper use etc. Though, as researchers, faced ethical challenges of privacy, to help them, we made every possible effort to assist by showing them how to use the cup.

3.9 Limitations

To the best of our knowledge, ours is the first study that presents evidence for a sensor design being tested with a range of bodily fluids, including menstrual blood. However, there are a few limitations of this work which can be categorized into data collection, sensor design, and in-the-wild usage respectively. During data collection, as we had assured the participants that we would collect data only during office hours between 8 am to 5 pm to minimize interruption in their daily routine, we could not observe the complete viscosity and color changes in the menstrual blood discharge during the entire menstrual cycle of the participant. The study of these properties with the proper segregation of the menstrual blood sample collected according to the days of the menstrual cycle would further help to improve the prediction model performance.

For the sensor design, the fabric we have used is a whisper sanitary napkin for all our experiments in this thesis. However, we do not know the specifications and processing of the absorbent material of the same. In our future work, we would like to study on other brands of

sanitary napkins and also with reusable napkins of different fabric materials.

For our experiments, we did not consider the horizontal pressure applied on the napkin when a female stands and walks which might have an effect on our sensor. Also, the vertical pressure applied on the napkin can vary depending on the activity, seating posture, seat material, etc., the effect of which has not been calibrated. The sanitary napkin might have been contaminated during the process of preparing the samples because of human intervention. A more sterile method of preparing the samples would be required for the prototype to be scaled for the end users' testing. The next chapter of this thesis looks into more on these effects of on-body conditions, side pressure applied on the napkin while doing different activities such as standing, sleeping, walking, and lying down.

Our setup used for all the experiments is a benchtop setup connected to a wired power source. Our sensor will be placed at a very sensitive part of a woman's body; putting a battery might be hazardous for health. However, it can be sporadically powered up using an NFC (Near Field Communication), which is a low-power wireless communication protocol that allows energy harvesting and establishing communication between the smartphone and the circuit for just-in-time sensing. The safe current limit for the human body is nearly 0.1 A [130], where the user can feel a mild sensation. However, the current depends on the resistance of the body and the applied voltage. Our circuit has 5.5 kOhm resistance and a 3.3 V power source, which gives the maximum current flow of 0.6 mA without the sensor connected, which is much lower than the sensing current limit of the human body. This current will further decrease after connecting the sensor, as the sensor will add more resistance to the circuit.

3.10 Summary

This chapter demonstrates the development of a menstrual blood volume sensor that can be used for menstrual blood volume measurement. The sensor design demonstrates the effect of different parameters that are important for volume sensing. The textile-based sensor has the advantage of being flexible and extensible for many different wearable applications. As this

sensor has already been tested with different salinity liquids, this can also be used to measure the volume of other body fluids, such as urine and sweat. The regression model created from 18 and 10 participants' intravenous and menstrual blood data works fairly well in predicting the volume values from the output voltage.

Chapter 4

Characterizing The Effect Of User Activities On Sanitary Napkin-Based Bodily Fluid Monitoring

Our first study proved that the sanitary napkin could be used to measure menstrual blood volume. The evaluation methods highlighted that blood volume could be measured with reasonable accuracy. However, the benchtop experiments can not capture the physiological and other real-world variations. In this chapter, we aimed to investigate the effect of physiological variations and activities on the sensor to move toward more practical scenarios. We do so by introducing a wearable sensor that we test in multiple settings.

We used iterative design methods to develop the wearable sensor. The ensuing studies establish the impact of the physiological variations and activity changes on the sensor. We conducted testing with mannequins to observe the effect of the side pressure applied by the legs on the sensor. We modified the design from a two-thread design to a six-thread design to address the lateral pressure issue of the napkin. We conducted user studies with 10 participants to collect quantitative and qualitative data to understand the effect of the body variation on the sensor and the users' experience with the sensing system.

The sensor design for bodily fluid monitoring is challenging because of variations in body

fluid properties and volume, physiological variation of individuals, the differences in the activities performed, and posture. Therefore for designing such a system, characterization of each parameter is necessary while the other variables remain the same. Benchtop testing can not capture the effect of on-body variation. The most important physiological variables that act on the sensor are the shape of the lower body, the weight / height of a woman, and the activities performed wearing the napkin. The sanitary napkin placement and shape change with the pressure applied between the legs. For example, if the lower body is heavy, the space between the legs is less, and the lateral force applied on the napkin between the legs is more. The location of the fluid drop changes with the activities of the wearer, such as when a user is in a lying down position, the fluid is dropped at the back of the napkin.

All these observations led us to the second research question

What effect do the activities performed by the user have on a minimally invasive, wearable sanitary napkin system built for the measurement of bodily fluid?

This chapter discusses the method we followed to address our second research question. The detailed description of the experimental design challenges faced and how we addressed those challenges. We have also described the user studies performed with ten female participants.

We started this chapter with an introduction to the wearable sensor design process and choosing the parameters for the experimental design and the user study. We then discussed the pilot studies performed for initial evaluation on benchtop settings and on mannequins. Section 3 describes the design of the Six-Thread Sensor, followed by the evaluation. In Section 4, we discussed the two user studies to investigate the effect of different activities and the experience of using our setup from the users.

4.1 Wearable Sensor Design

The body shape changes the sanitary napkin shape when a female uses it. Various forces are applied to the napkin depending on the shape and posture as shown in Figure [4.1](#). Also, the activities of the user play an important role in changing the pressure point on the napkin.

With the lower body movement of the user, the sanitary napkin also changes its shape as it is tightly attached to the undergarments of the user. This movement of the sanitary napkin relative to the body creates variation in the fluid-dropping location on the napkin. The analysis of all kinds of force on the sensor is a complex and time-consuming task requiring a variety of sensors. However, the two most critical forces are vertical force from body weight and lateral force from the legs.

In this thesis, the two vital parameters for analyzing the effect on the sensor are physiological shape and activities. To understand the impact of these parameters, we conducted user studies with participants.

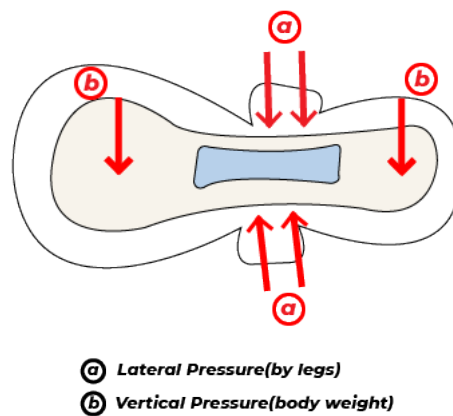


Figure 4.1: Different Types of Pressure Applied on the Napkin

A user can perform various activities in a day but can't notice the activity change every time in a day. If the activity changes with time, we can not capture the effect on the sensor for the activity change. Therefore, to investigate the effect of an action, the user should perform that activity for a specific amount of time. We chose four activities standing, sitting, walking and lying down.

Except for the impact of these physiological variations and activities, there are changes during menstruation in the menstrual fluid composition and flow. Since the sanitary napkin sensor measures menstrual fluid volume, the best way to conduct the study is with menstruating users. However, there are several reasons why we have not used them in the first place. Our

study in this thesis is a significant step towards investigating with menstruating users.

- The menstrual blood fluid composition and volume changes with days of menstruation for each user. Varying fluid properties may create an impact on the sensor, and the effect of the activities and body shape can not be captured.
- To understand the effect of activities, the amount of fluid should be known. However, there is no easy way to measure the fluid volume discharged from the body in real-time.
- Collecting, storing and dropping the known amount of real fluid on the napkin is also not possible due to the risk of infections.

Another way is to experiment with intravenous blood as conducted in benchtop experiments. However, the experiment with intravenous blood is risky for the following reasons. First, it may cause infection as it touches the user's body. Second, it is not feasible to draw intravenous blood from the same user because the intravenous blood starts to clot within 7 minutes. Third, due to Covid 19 pandemic experimenting with blood is not safe for users and researchers. We chose normal saline (0.9% NaCl) as the experimental fluid as it is readily available and extensively used to conduct numerous experiments in earlier research.

To make the sanitary napkin sensing system wearable, the conductive threads of the sanitary napkin must be connected to the electronics module. The limited availability of soft, and hard connectors, cost and difficulty of creating those connections led us to explore various other design options. Cost, time of sample preparation, and robustness guided our explorations. Copper tape, Electronics ink and glue are used for creating conductive traces as these were easy to connect and make the traces. However, these materials are very easily scraped off from the napkin and can not withstand wear and tear, creating disconnections and data loss. Other variations of conductive threads and fabrics are strong and robust but require higher design time for each sample and are costly to dispose of with the sanitary napkin. We tried metal clips, buttons and rings to connect the conductive threads traces with the wire, but they were time-consuming. Automating the complete design process was not possible due to manufacturing limitations.

We started by carrying forward the design of the sensor from previous studies to make it a wearable system. This sanitary napkin sensing system was to be worn by a woman on the sensitive part of the body. Also, the system should be robust to withstand the stress and strain due to various activities performed by the wearer and their body shape. Therefore safety and comfort were our primary concerns.

To make the soft-to-hard connection from the conductive thread to the electronics module, we attached a thin jumper wire which we reused after sterilisation for all user studies and experiments. For data collection powering up the circuit, we used a Teensy 3.2 microcontroller and a 3.7V lithium-ion battery. We made a fluid dispensing system to dispense 0.5 mL of fluid on the napkin through a thin pipe attached to the napkin. After completing this design modification, we tested the system initially on a benchtop setup and then on the mannequin. To resolve the challenges of fluid dropping location due to side pressure applied on the napkin, we redesigned the sensor and conducted user studies with ten female participants. The following sections describe the experiments and the user study in detail with the analysis of the results.

4.2 Pilot Studies

The goal of this study was to examine if the sensor behavior remains the same as in previous test conditions.

4.2.1 Pilot Study On Benchtop Setup

4.2.1.1 Setup

For the pilot study, we created 5 samples of two-thread designs (Threads are 4 cm apart) using 3rd absorbent layer of Whisper XL+ sanitary napkin. We designed a prototype (refer to figure [4.2](#) (A)) of a curved surface imitating the lower body shape of a woman (measurement taken from a woman with BMI 20) using an MDF sheet. We created a dispensing system, which consists of a 3D printed syringe dispenser using a screw and plunger and a servo motor for flow control (refer figure [4.2](#)(B)).

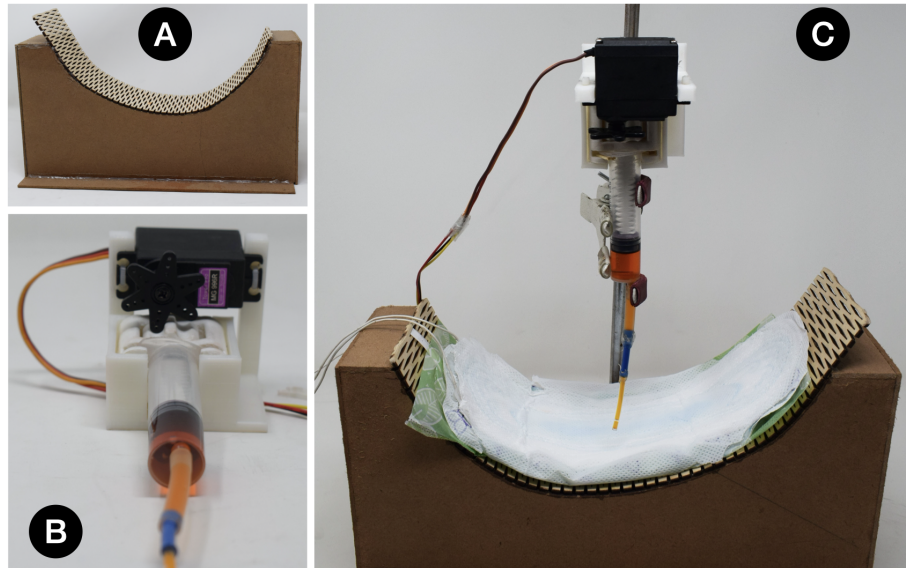


Figure 4.2: Experimental Setup

4.2.2 Experiment Method

The napkin was placed on the curved surface and dropped 0.5mL of fluid each time till 6.5mL at the centre of the napkin through the fluid dispensing system. We recorded data for 10s after the 20s of dropping the fluid to let the fluid absorb in the napkin. Figure 4.2(C) shows the experimental setup of the system.

4.2.3 Pilot Study With Mannequin

Benchtop experiments on a curved surface can replicate the orientation of the female lower body; however, the pressure applied between the legs can not be simulated using that. Therefore, we performed experiments on the mannequin to understand the effect of body shape on the napkin.

4.2.3.1 Setup

We used an inflatable female half-body mannequin on which we put on disposable innerwear and created 5 samples of the two-thread sensor for this experiment. A thin pipe was attached along with the sanitary napkin from the dispensing system to drop the fluid on the sanitary

napkin. Figure 4.3(A) shows the sanitary napkin system that was used for testing with the mannequin. The data recording setup remains the same as the previous experiment.

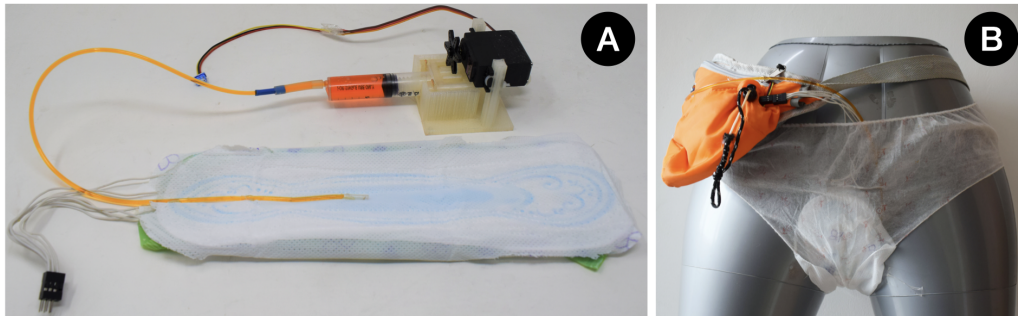


Figure 4.3: Sanitary Napkin Setup for Testing With Mannequin

4.2.3.2 Experiment Method Update

We attached the napkin to the innerwear of the mannequin in the same way as a woman wears the napkin (refer to figure 4.3(B)). The circuit and the dispensing system were kept inside a fanny pack. The fluid-dropping method and data collection were the same as before.

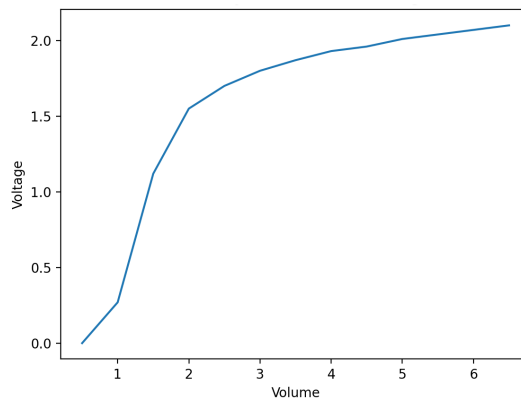


Figure 4.4: Benchtop Experiment with Two-thread Design

4.2.3.3 Results and Analysis

Figures 4.4 and 4.5 shows the average output voltage variation with the fluid volume for benchtop experiments and mannequin experiments, respectively. We can observe that the benchtop experiments follow the same trend as shown in paper 35.

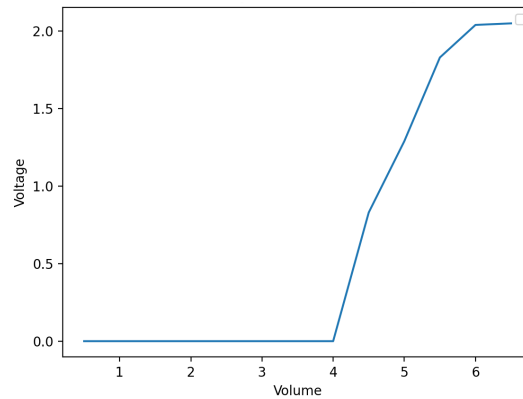


Figure 4.5: Pilot Study with Two-Thread Design with Mannequin

From the mannequin experiment results, we can see that the initial volume detection starts at a higher volume than the [4.4](#). During the experiments, we observed that due to the shape of the lower body of the mannequin, the sanitary napkin was folded from the sides. Therefore, the fluid was dropped at the sides of the napkin instead of the centre of the napkin, and the two threads were not getting connected. This led us to redesign the sensor.

4.3 Six-Thread Sensor Design

To overcome the challenge of fluid dropping location at the side, a naive approach would be to reduce the gap between the conductive traces. However, that would increase the probability of volume not being detected at the sides.

Our resolution was to add two more lines at a 1cm distance on each side of the centre lines. The new sensor design is shown in figure [4.6](#). Each pair of lines at a 4cm gap is referred to as a block (Please refer to figure [4.7](#)), and we will refer to this design as six-thread design. When the fluid dropped, any one of the three blocks got selected depending on the dropping location, and the sensing started. Figure [4.7](#) shows the illustration of the six-thread design with the circuit module and motor driver.

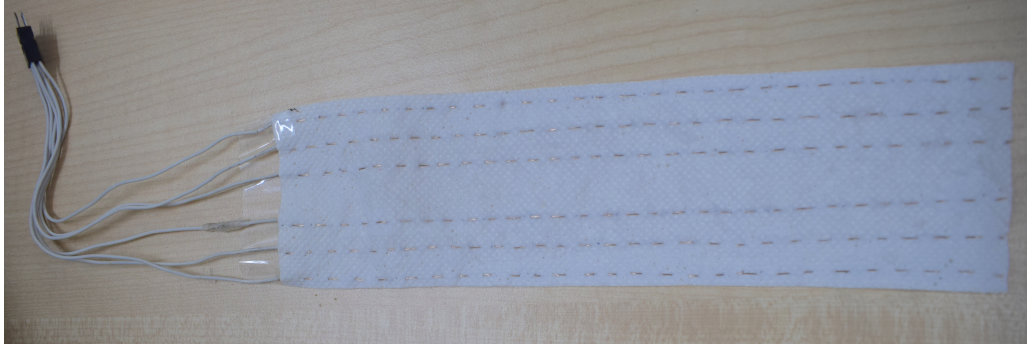


Figure 4.6: Six-Thread Sanitary Napkin Sensing System

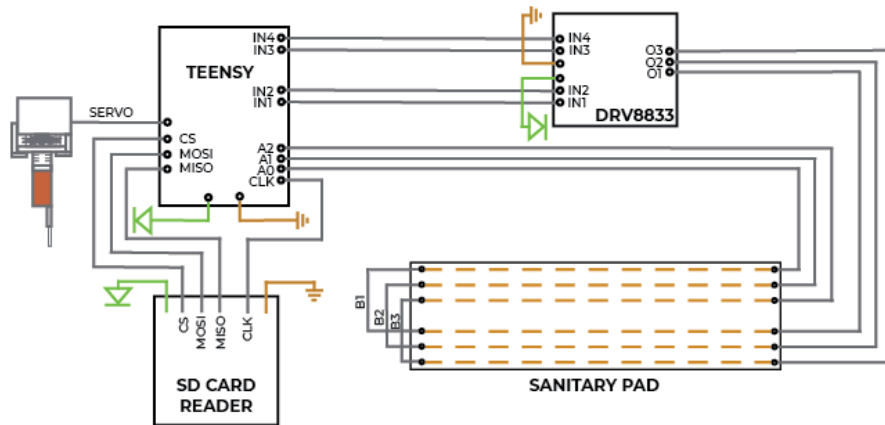


Figure 4.7: Schematic Diagram of the Sanitary Napkin Sensing System

4.3.1 Benchtop Experiment To Compare The Six-Thread Design With Two-Thread Design

To compare the results with the two-thread design and to investigate whether it can measure the fluid if dropped at the side, we conducted benchtop experiments with a six-thread design.

4.3.1.1 Setup

We created 10 samples of six-thread designs for this test. The fluid dispenser and the data recording setup remain the same.

4.3.1.2 Experiment Process

We placed the napkin on the curved surface and dropped fluid at the center of the napkin for five samples and at the side of the center of the napkin for the remaining five samples. The fluid dropping and the data collection method remain the same as before.

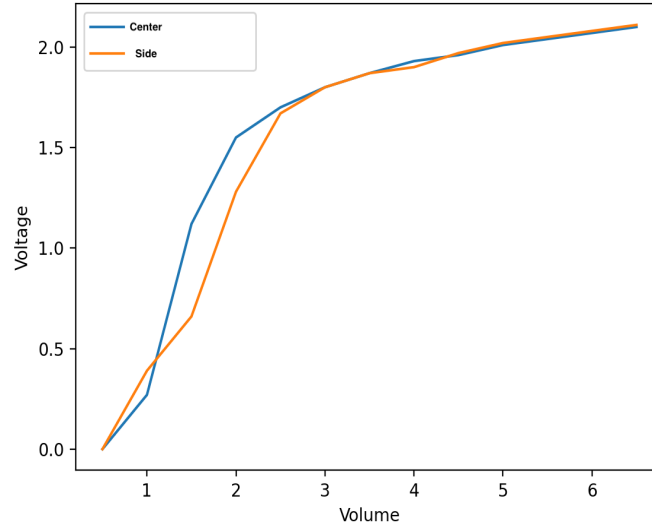


Figure 4.8: Comparison of the Six-Thread Design with Two-Thread Design on Benchtop Setting

4.3.1.3 Results and Analysis

Figure [4.8](#) showed the comparison of the average output voltage variation of the six-thread design when the fluid was dropped at the center and at the side. We can observe that the variation remains the same for both cases. This motivated us to move on to the next set of experiments on the mannequin and with users.

4.3.2 Experiments with Mannequin

The goal of this experiment was to verify if the volume detection starts early with the six-thread design on the mannequin.

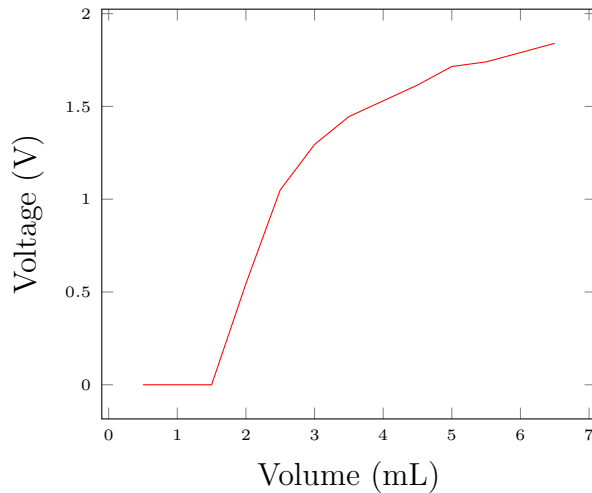


Figure 4.9: Experiment with Six-Thread Design on Mannequin

4.3.2.1 Setup

We created five samples of six-thread designs and performed experiments following the same setup as before.

4.3.2.2 Experiment Method

We follow the same method as the two-thread design experiment [4.2.3.2](#) for conducting the five tests on the mannequin. Figure [4.9](#) shows the results of this experiment. We observe that the detection starts early than the two-thread design [4.2.3.3](#)

4.4 User Studies

We conducted two user studies with the participants. One is to understand the effect of activities on the sensor and the second one is to understand the user experience. We analyzed the quantitative and qualitative data collected from these studies.

4.4.1 Study 1: Effect Of Activities

The experiments conducted till now show the effect of shape and orientation. However, the on-body conditions, activities, and movements can not be simulated by the mannequin. Therefore,

Table 4.1: Participants Information

Participant Number	Age	Height(cm)	Weight(Kgs)
P1	38	165	58
P2	31	152.4	56
P3	22	158	42
P4	32	150	54
P5	35	151	58
P6	30	166	59
P7	28	153	56
P8	23	152	57
P9	28	165	52
P10	28	162	55

we conducted an extensive user study with four different activities standing, sitting, walking, and lying down conditions for the user to understand the effect on the sensor. We conducted experiments with 8 samples for each activity, and each sample experiment took 7.15 minutes. In total, the study was around 4 hours long. We divided the study into two or four-part for an expected doable time of one to two hours for the user’s comfort and availability. The experiments were conducted in a separate room with one participant to maintain social distancing and sanitation.

4.4.2 Participants And Setup

Gathering participants for this IRB-approved study was the most challenging task because first, very few women were physically available due to the ongoing Covid situation; second, women did not feel comfortable taking part in this kind of study where physical contact is required even though we assure them about the sterilization and sanitation. Further, the study procedure was time-consuming; therefore, even if some participants agreed to participate, they could not finish the study. Table [4.1](#) shows the age, weight, and height of the participants chosen for the study. We provided \$3 as compensation to the participants.

We did convenient sampling to recruit participants. We explained the purpose of the study and the experiment procedure to them and received their consent. We collected their convenient time and phone number for contacting them. The same setup was used as before for

collecting data. The fluid dispensing system, battery, and data recording module were placed inside a fanny pack. We asked participants to wear sanitary napkin as they wear them during menstruation. The wires coming out of the napkins are connected outside the lower garments with the rest of the electronics. The small pipe used to dispense the saline was connected to the dispensing system. The sanitary napkin was touching the user's body which we disposed of after the experiment. The electronic elements were not touching the intimate body parts. The fanny pack was sterilized before every experiment. We used disinfectant wipes to clean the wires, and pipes and disinfectant sprays to sanitize the fanny pack and other elements. We dried them entirely before using the circuit again to avoid any potential short circuits. Figure 4.10 shows the different activities of a user wearing the setup. We color-coded the connections to make them easier to understand by the participants. Social distancing was maintained while conducting the study, and sanitizer and disinfectant were kept near the participant to be used at will.



Figure 4.10: Activities Performed by the User

4.4.3 Procedure

We divided the 4-hour study duration into one hour each. We demonstrated how to wear the setup, make the connections, and the activity process before each study to all users. Since the connections were outside the lower garments, we let choose the user if they wanted to make the connections themselves or if they wanted us to help after wearing the napkin. Most users prefer connecting it on their own. However, for those who faced difficulty initially in making the connections, we helped them.

- **Standing** The study started by explaining the complete procedure and demonstrating

the connections. Participants were in a standing position during the study, and we asked them to wear the napkin in the same way they wear it during their menstrual cycle.

- **Sitting** During the sitting procedure, participants were asked to sit in an upright position on a chair.
- **Walking** We asked participants to wear the setup and walk at a normal pace for 7.15 minutes on a 4-meter-long walking area. Participants were walking continuously for the study duration.
- **Lying Down** Participants were asked to lie down on their backs after wearing the setup on a mattress. We asked them to start the system after they took the lie-down position.

4.4.4 Observations

Few participants allowed us to observe them during the study while for others we left them alone in the room after explaining the connection details and the process. Here we listed the observations during the study.

- For some participants we helped make the connections when they were facing difficulty. We observed that participants were comfortable during the experiment and started observing either their phones or working on their laptops (while doing a sitting activity).
- We conducted 8 experiments of one activity on a single go and it took only two to three minutes to change the setup.
- We made six pins JST male-female connector for easy and robust connections and color-coded it to make it easy to understand one participant who faced difficulty in making the connections. We observed that the participant left some pins unconnected and was making an incomplete connection. Therefore, we had to repeat one or two experiments.
- Some participants felt uneasy during the first experiment when fluid dropped on their napkins for the first time. This is due to the fear of leaking fluid on their lower garments

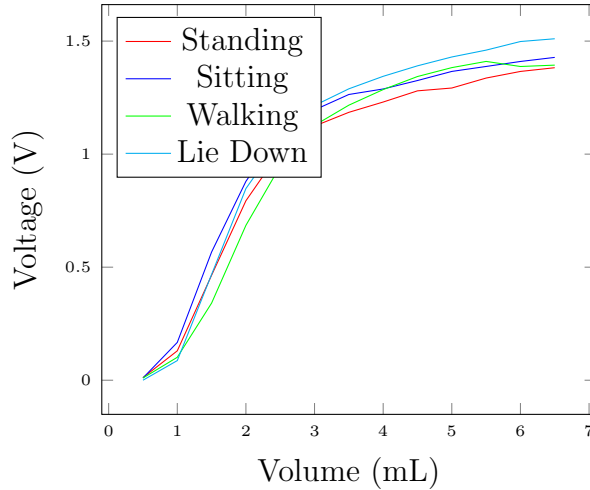


Figure 4.11: Analysis Across Activities

however when we assure them to check, they were comfortable that it is not leaking outside the napkin.

4.4.5 Results and Analysis

We performed an analysis of different activities for each user. Figure 4.11 shows the change in output voltage for fluid volume change for different activities. It can be observed that the trend remains the same for all the cases. Figure 4.12 and 4.13 show the average output voltage variation of all participants for each activity. The error bar shows the standard deviation of the variation at each volume point. We can observe that the output voltage increases with the added amount of fluid for all users in each activity, and variation is similar across the activity. The sensor performance remains uniform for all users and activities.

4.5 Study 2: User Experiences From Wearing The Sensor Pad

To understand the user experience of using this sensing system, we conducted semi-structured interviews with female participants who participated in user study 1. The age and BMI of the participants are shown in table 4.1.

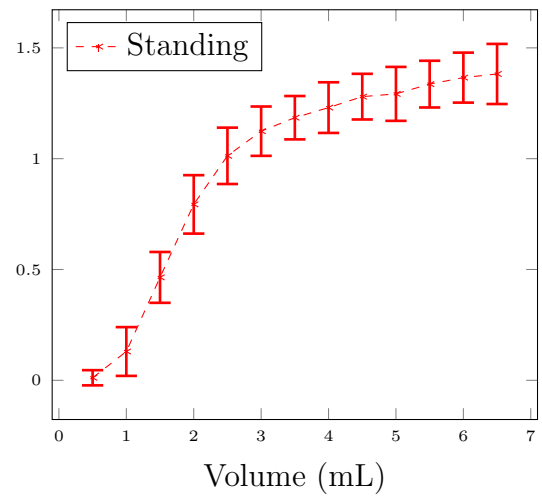
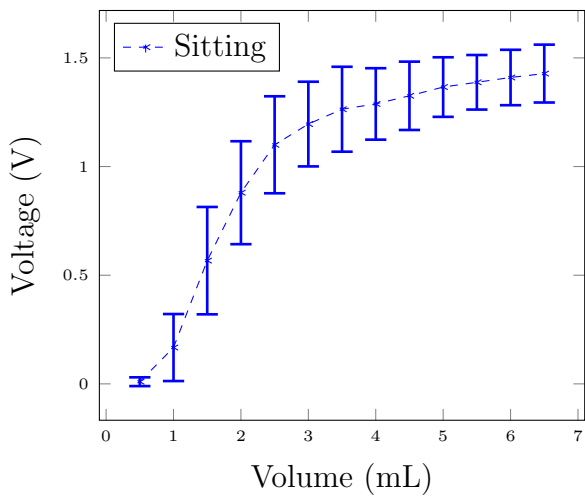


Figure 4.12: Interpersonal Variation of Sitting and Standing Activity

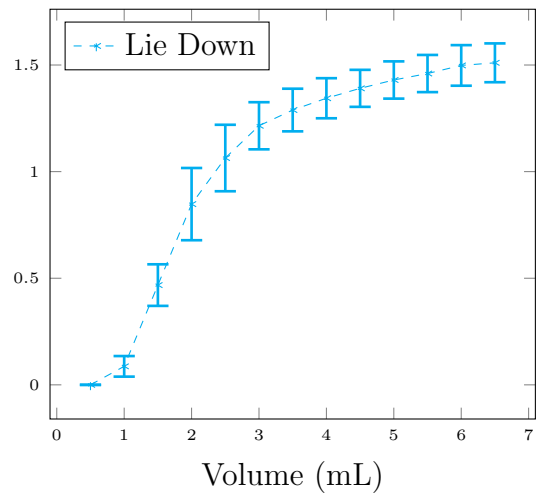
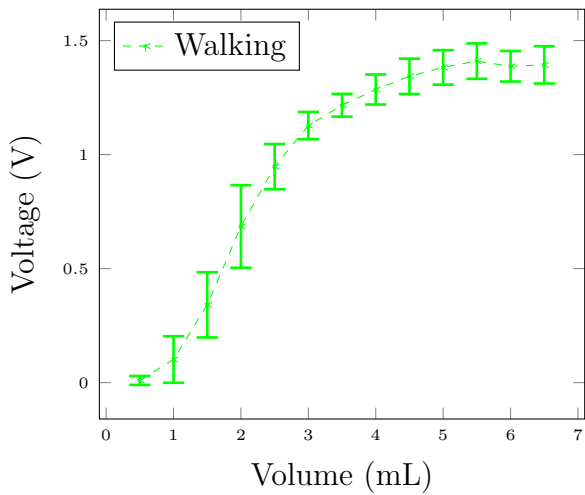


Figure 4.13: Interpersonal Variation of Walking and Lying Down Activity

4.5.1 Methods

All interviews were conducted over the phone in English or their native language depending on the participants' comfort levels. Each interview took 10-15 minutes. Two participants were not available for the interviews due to unavoidable constraints. We describe to the participants the purpose of the interviews and the process. The goal was to understand the participant's overall experience, particularly focusing on if the system was comfortable to use and if it was easy to perform activities wearing the system. We started interviews by asking questions like

- *How did you feel about the system and was it comfortable?.*
- *Was it easy to wear the napkin and make the connections?*
- *What is the comfort score you would give to the system from one (least comfortable) to five (most comfortable).*
- *Was it comfortable to perform activities wearing this?*

4.5.2 Analysis

Interviews were transcribed and translated into English when necessary for analysis. We categorised the responses of the participants according to the questions.

Our goal was to gather information regarding the feelings and convenience of the user about the system and to perform different activities wearing this. Therefore we categorize the questions into 1. The comfort of use, 2. Easy to use, 3. Comfortable performing activities.

All participants mentioned that the system was comfortable to use. Participant (U2) said *"it felt similar to the napkin we wear"*. Regarding the ease of use and making connections, all participants agreed it was easy to make the connections. One participant (U1) mentioned *"Initially I did not understand the connection, but when you explained and showed the colour code, then it was easy"*. To better understand the user's experience, we asked participants to give a comfort score between One (least comfortable) to Five (most comfortable) to the system. 8 gave a score of five, and 2 gave four. Regarding the most comfortable activity, 8 preferred

Table 4.2: Summary of Interviews

Questions	Comments
Comfortable	10 (Yes)
Easy to wear	10 (Yes)
Comfort Level	8 (5), 2 (4)
Activities	8 (Sitting), 2 (Walking)

sitting and 2 preferred walking. Table 4.2 shows the summary of the analysis of the feedback collected from the participants. An interesting observation was that this activity preference is related to the work they do in their daily life. For example, students preferred sitting activities as they were performing their usual tasks of reading and writing on their computers. At the same time, staffs who are generally more active during the day prefer walking, as a participant (U2) said *"Our work involved walking, so I prefer walking"*. Also, the boredom and discomfort of standing in one position and lying down may have influenced their choice of activity. To understand the system's usability and get better insight into the user's preference, we asked questions like *"if you are given this wearable system to track your menstrual health would you like to use that?"*. 8 said yes. 2 said maybe because it depends on the situation.

4.6 Limitations

We are the first ones to conduct such an extensive user study with a sanitary napkin sensor. However, this study has a few limitations related to participants and the experiment process. We have categorized these limitations into sensor design, and user study limitations. For designing the sensor, we have used Whisper XL+ sanitary napkin which is a well-known sanitary product from Proctor & Gamble. We assume that the napkin is manufactured automatically through the machine; the fabric and other parameters remain the same for all the napkins. However, we do not know the type of fabric materials and manufacturing details.

We recruited participants through convenient sampling due to limited users' availability. Though we have females with different body shapes and weights in our recruitment, we could not recruit participants in an equal ratio of different body weights and shapes to remove any

potential bias from our data. We have conducted experiments in a separate room to maintain participants' privacy and social distancing. After describing the experiment method and explaining the connections, we left the participants in the room for their comfort; therefore, we could not capture any sudden posture change during the experiment.

We used normal saline for our experiments which is the most similar to our body fluid, such as sweat. However, the viscosity of saline is different from vaginal discharge, which may have an effect on the absorption of the liquid on the sensor.

During our experiments with mannequins and users, we attached the pipe to the napkin for fluid dispensing to imitate body fluid discharge. However, it is only a close approximation of the actual scenario of liquid discharge from the vagina, which may affect the fluid-dropping location on the napkin.

Our study was a step forward toward designing a smart sanitary napkin-based body fluid monitoring system. In future, we would like to do the study with more participants in a longitudinal manner where the user will wear the napkin for a longer duration of 5-6 hours. Further next step could be to investigate the effect of various other bodily fluids.

4.7 Discussions

Our wearable sanitary napkin system is a preliminary yet significant step towards female intimate wear devices and innovative period technologies. The design process, challenges, and methodologies discussed in this thesis can support the ongoing exploration in the area of wearable sensing, personal care devices, and technologies.

The wearable sanitary napkin design was an iterative process where we designed the napkin in our lab with extensive sterilization and safety measures. Though we reached out to manufacturers in India to manufacture the napkin to our specifications, we identified several challenges and implementation gaps.

The existing technology gap between the sanitary napkin manufacturing industry and Electronics design was the primary roadblock to manufacturing the sanitary napkin sensor. The

manual process did not work for the knowledge translation gap between manufacturers and researchers. The automatic process has its own challenges. For example, any changes in the prespecified manufacturing process (integrating stitching with conductive thread, attaching the connectors) were expensive and tedious to set up.

In the wearable design, a sanitary napkin was to be connected to the circuitry for data collection and analysis through conductive wires. These wires are to be connected at one side with the soft conductive thread and on the other side with a hard electronics module. Since there is no robust hard, soft connector available off the shelf, we had to make each connection manually, which was time-consuming.

Additionally, no technology is available to measure fluid discharge from the body. Also, no small and precise dispenser was known to conduct an experiment like this. Therefore we had to design a 3D-printed dispenser to drop a specific amount of fluid.

Although these challenges exist, we hope that with new technologies and with growing e-textile industries, it will be possible in the future to address these concerns and focus on other design methods.

4.8 Summary

In this chapter, we described the development of the sanitary napkin sensing system. We presented the design elements and constraints of the system. We also discussed experiments and user studies that we performed to evaluate the system. We have shown the sensor performs uniformly across activities for all users. The user experience study highlighted that the prototype was comfortable to use and performed the activities.

Chapter 5

Exploration of Battery-less Wearable Sanitary Napkin System Design

Our previous studies motivated us to explore the third research question *Is it technically feasible to create a battery-less wearable sanitary napkin system design for in-situ data collection?* To explore this we design a battery-less wearable sanitary napkin system that can be used for data collection while in use with menstruating users. In this chapter, we describe our initial exploration and data collection using a battery-less wearable sanitary napkin system designed using NFC technology. We investigated the NFC communication range with three different fabrics and two different layers and showed the complete wearable system design process. Through a pilot study with a few users, we showed that this kind of system design is technically feasible.

Section 1 describes the sanitary napkin prototype with an electronic module that enables data collection through NFC technology. Section 2 presents the mobile application development. Section 3 presents the initial investigations on the range of NFC communication with different types of fabric material to show NFC communication is possible. Section 4 presents the pilot user study with menstruating users.

5.1 Wearable Sensor Design Using NFC Technology

The broader goal of this exploration was to create a battery-less wearable sanitary napkin system for monitoring blood loss volume in which a user can collect and monitor their menstrual health privately. However, in this thesis, we limited our explorations to investigating NFC communication with a smartphone. The development of this system has two parts- 1) Sensing System and 2) a Mobile Application. The Sensing System consists of a Sanitary napkin sensor, an attachment, and a data collection module to collect data and communicate with the mobile application. The communication range of the NFC has been examined with a variety of fabric materials. We designed a simple mobile application to collect and store data.

Sensing System The data collection module contains a microcontroller, NFC antenna with tag IC [131] and a resistance of 5.5 K. We used Red Bear BLE Nano [132] from Sparkfun NRF 52832 board to make it smaller. NFC antenna wirelessly powers the circuit and transfers data to and from the sensor system to smartphones. The NFC antenna NXP Ntag I2C IC (NT 3H1201) has two interfaces, RF and I2C, to communicate with the reader device (NFC enabled Smartphone) and I2C interface (To communicate with a microcontroller). The microcontroller reads sensor data and transfers it to the Smartphone through the I2C interface. We designed a custom-printed circuit board and 3D-printed casing to accommodate the NFC antenna and Microcontroller (refer to figure). When the system comes into contact with the Smartphone, it powers up the complete design and starts collecting sensor data. Figure [5.1] shows the initial prototype of the PCB design and antenna.

We also designed a 3D-printed casing to cover PCB and the antenna. Figure [5.2] shows the image of the closed and open casing. Figure [5.4] shows the complete system with a sanitary napkin sensor, attachment, and NFC module.

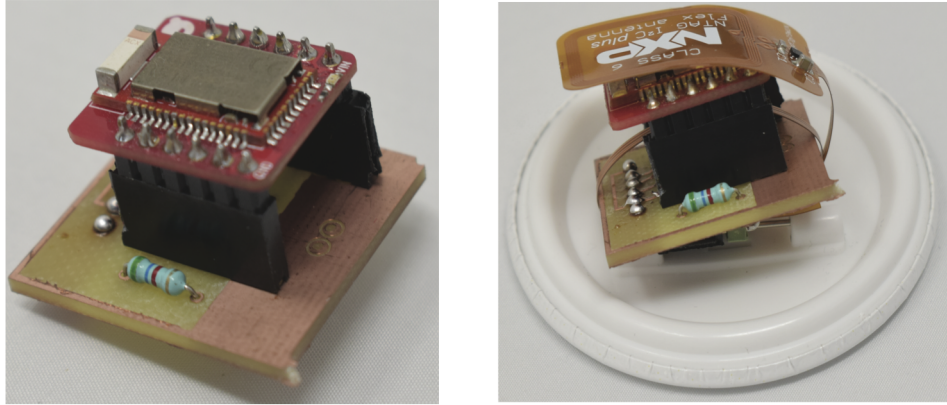


Figure 5.1: PCB and the NFC Antenna Connected



Figure 5.2: 3D Printed Casing Closed and Open View

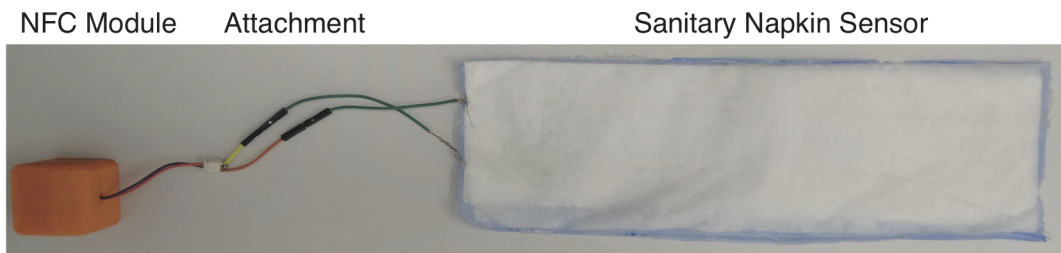


Figure 5.3: Prototype of the Battery-less Wearable Sanitary Napkin System

5.2 Mobile Application

The primary purpose of the mobile application is to detect the NFC tag then, read the data and then store it locally. Also, the app is used to input users' personal details and give notifications when it is time to record data. Near Field Communication has been chosen for data transfer because these sets of protocols utilize low energy radio waves of frequency 13.56 MHz for data transfer. Therefore, although the maximum distance of transmission is very low at about 4 cm, these protocols are much better than other protocols, such as Bluetooth, which rely on transmission media of higher energy for the task at hand. The low energy requirement allows the tag module to work without any external power, relying entirely on the power received from

the mobile phone's antenna via inductive coupling.

The process of intercepting the tag and reading the data has been described below:

- Upon encountering a nearby tag, the android operating system launches an intent.
- This intent then searches for an app that can interface with the NFC device.
- As The MenstruPal App has been registered as an app that can perform the required operation, the android ecosystem launched the app.
- Then, the app switches activities to reach the activity which interacts with the newly encountered tag.
- First, authentication is carried out using a 32-bit password. Once the authentication is success full then, the app initiates a reading process.
- Records are read from the tag's memory using NFC protocol in chunks of increasing size depending on the robustness of the current connection. As the records are read, they are displayed to the user, indicating that a read is in process. Simultaneously these records are written into text files that are stored in the phone's internal storage.

5.3 Pilot Studies With Fabric Materials and Layers

The data collection module could be attached in various ways to the lower garments or may be placed inside the pockets. Since the range of NFC communication is short, about 4 cm, we started exploring how the range varies with various smartphones and with a variety of fabric materials. We considered two smartphones, Google Pixel [133] and One Plus One [134], for our experiments. The fabric materials we chose are Felt, Cotton, Denim, and Spandex, as these are the most frequently used lower garment materials.

Fabric	Single Fabric Layer	Two Fabric Layer
Felt	1 cm	0.75 cm
Cotton	1.25 cm	1.25 cm
Denim	0.5 cm	0.25 cm
Spandex	1 cm	1 cm

Table 5.1: Phone Used: One Plus one

5.3.1 Experiment Setup

Two samples of size 6 inches by 9 inches were prepared from each of these fabrics. The size of the material chosen is the maximum size of antenna possible. We used a vernier caliper to measure the thickness of the fabric and the distance between the reader (smartphone) to the antenna. Multiple wood sheet of 3 mm thickness was used to create the gap between the tag and the reader.

5.3.2 Experiment Method

The tag was placed in a fixed position on a table; the vernier caliper measured the thickness of the single-layer fabric sample and placed it on top of the tag. The reader was placed parallel to the tag at a distance of 4 cm (Maximum distance NFC should work). The distance between the reader and the tag was decreased by 3 mm every time until communication started between the tag and the reader. The distance at which it starts communicating is measured. We increased the number of layers and repeated the experiment for two layers for each type of fabric.

5.3.3 Results

We observed that the safe range for NFC communication varies with different phone brands. It also depends on the clothing material and the layer of materials considerably. These experiments inform that the battery-less menstrual volume monitoring system is also possible and suggests a number of future directions.

Fabric	Single Fabric Layer	Two Fabric Layers
Felt	2 cm	2 cm
Cotton	2 cm	2 cm
Denim	1 cm	1 cm
Spandex	2 cm	2 cm

Table 5.2: Phone Used: Google Pixel

5.4 Pilot In-The-Wild Study With Menstruating Participants

To explore the feasibility of the overall system and the data collection process, we conducted an in-the-wild pilot study with five menstruating participants for one menstrual cycle. The institute IRB approved the study. The age range of the participants was 19-35 years. The participants were given goodies of \$1 for participating in the study. The participants self-collected the data through our system during their menstrual cycle.

5.4.1 Process

We conducted introductory sessions with females in our institute to demonstrate the system and data collection process. We gathered participants' names, phone numbers, and the next menstrual cycle date from the females who attended the session and were willing to participate in the study. We contacted each participant three days before their menstrual cycle date, took their informed consent, and gave the complete system with 12 sanitary napkins, an NFC data collection module, along with an NFC-enabled smartphone for use. Each napkin was to be used for six hours, and we wanted to collect the first three days of data; We provided more to some participants when needed. We demonstrated how to use the wearable sanitary napkin system to collect data and assured them of assistance when they used it. Participants were instructed to collect data as many times as they could during the day but a minimum of one data/hour for the three days. Participants raised concerns about nighttime data collection, but we instructed them to collect before and after waking up from sleep. After the data collection,

we also collected feedback on the system and about the data collection process. We asked participants about their data collection experience -

- *"How easy was it to collect data?"*
- *"Was there any difficulty in connecting with the mobile app?"*
- *"Was there any difficulty in using the app?"*
- *How they felt about using such a system - for example, was it weird to show the box?"*
- *What do they think about the social acceptability of such a system?"*
- *"Any other experience they wish to share with us."*



Figure 5.4: User Wearing The Battery-less Sanitary Napkin system

5.4.2 Findings & Discussions

Scope for Batteryless System Design Based on the exploratory investigation results, we see NFC has excellent potential for future research in wearable sensing and batteryless design of sanitary napkin systems. All the participants mentioned that the system was comfortable to use after using it. However, three participants were concerned about the napkin material being very soft and thin when we gave them the napkin set and mentioned *"I have a heavy flow, and I think the material is too thin for me, I might have to change it before five hours"*. We assured them that they could change it whenever they needed to. During the study, we

realized that the material was indeed very soft and could not last longer than two hours for most of the participants, and we provided more napkins to the users who needed them. Four participants said it was easy to collect data and the app. Three participants said that they think it is okay to show such a small box, but two others said that they do not want to show the box as one of them mentioned *"I do not want to show this outside as it might create curiosity to others"*. About the social acceptability question, participants told us that they think it will be acceptable as many people use lots of wearable devices these days.

With this in the ground, we think that this is a promising FemTech device with a lot of opportunities. However, several challenges need to be worked on. One challenge with this technology is the limitation of communication range and the antenna direction. The placement of the smartphone NFC antenna and the tag antenna should match the direction and needs to be in the range of 2 cm, as can be seen from the results in tables [5.1](#), [5.2](#) for good communication which is relatively low. There are other manufacturing challenges; as we mentioned earlier that for mass production, a change in the sanitary napkin manufacturing process is required, which would not be easy.

Besides these, the wearable napkin system and the in-the-wild study have their challenges, such as there is no easy way exist to get the ground truth data about menstrual blood loss monitoring from our bodies because there is inter-person variability in menstrual blood property and intra-person variability of menstrual blood with the days of menstruation.

We observed that the system was robust to withstand the various physical forces applied to the napkin and the connections during the activities for three days. However, the activities change during the day, and the data collection frequency change depending on users' convenience, making it challenging to analyze the data. Moreover, we also realized that data should be collected regularly for evaluation and analysis. Therefore, either the system must be designed to gather data automatically without any user interruption, or the participants should be recruited so that they collect data at a regular frequency. Moreover, controlled real-life experiments should be conducted to understand the performance better.

Chapter 6

Discussions

This research encourages the debates among the HCI and women's health around menstruation [135-137], self-monitoring devices [138-140] and the limitations and inadequacy of these technologies [141,142]. Several recent researchers [143,144] and wearable devices [145,146] are aiming at understanding menstrual cycles and overall women's physiological changes around the life cycles. It is understood that menstrual cycles affect self-hood across a simplistic body-mind division or reproductive imperative, engendering complex self-management techniques, including monitoring, hypothesizing, intervening in medical appointments, adjusting schedules, and interpreting social interactions of a woman [147].

This research contributes to estimating the true measures of menstrual volume in real time. The two major limitations of the state-of-the-art menstrual volume measurement systems are - the procedure is time-consuming [148], and it requires the collection of all the sanitary products, and the other method is subjective [15]. Collecting sanitary products and storing them for measurement is a costly, time-consuming process. Moreover, inadequate knowledge of proper handling and disposal of these materials may create the risk of infections. Our solution allows the collection of true menstrual volume measures in real-time without the need to share the menstrual products.

Our research in this thesis expands the knowledge base of menstrual health monitoring practices. For instance, it adds another dimension to the existing mobile-based menstrual tracker

where women gather real-time monitoring data along with other self-reported body conditions like stress, pelvic pain, headache, nausea, etc. [149–151]. Our work adds a new dimension to HCI research in personal care interventions and health care devices, prioritizing opportunities specific to women’s health and well-being. For instance, based on the variation in menstrual blood and its flow, a woman can now make an informed choice of selecting physiological activities and movements.

Our research provides objective measures of menstrual data who seek relevant guidance on menstrual health. By augmenting true measures of menstrual volume and cycle tracking, it provides a better understanding of one’s body [152], helps to avoid stain stigma [59], and birth control [153]. It enables women to connect their body’s objective measures to the subjective experience; for instance, one can correlate that with higher menstrual leakage volume - nausea, weakness, or headache increases. This information is medically relevant to rule out the causes of certain health conditions and diagnostics. Recent research on menstrual tracking and sharing practices [154] highlighted the need for a better design approach for deeper understanding and customization of the menstrual cycle and data sharing. Our work builds on and supports this argument by allowing users to share objective information of menstrual data who seek relevant guidance on menstrual health.

The objective data collection on menstrual volume provides opportunities for AI-assisted model generation for personalized treatment and predictions. This research can reduce the overarching gap of the need for a human-centered artificial intelligence approach for model and data provenance, transparency and explanations of uncertainties, and the prioritization of privacy in menstrual trackers [155]. To date, no real menstrual volume data were collected by any means to consider AI-assisted model generation for menstrual health and provide recommendations on health issues for women.

The volume detection and leak detection from the sanitary napkin assist impaired women by providing an objective volume of information to be shared with healthcare practitioners and others. It also enabled them to manage the distress and stigma from the stain by giving feedback on upcoming cycles, when to change the napkin, and possible leakage from the napkin,

to be prepared for the upcoming cycle. Recent article [156] documented how a woman with a disability faces challenges due to inaccessible bathrooms or sinks, lack of menstrual education, shame and stigma around disability and menstruation, limited mobilities, pain conditions and sensory issues. Inserting tampons or menstrual cups require the use of the arms, hands, and fingers and is not always a viable option for some disabled females. Family members can not help them because of the privacy and shame related to this body material. Another important barrier for many impaired women is that they can not give subjective information on menstrual volume to medical practitioners due to the inability to see the stain on the napkin. Our research makes a strong contribution to the field of assistive technologies as well.

This dissertation can help address the knowledge and skill gap between research and industry. We broadly classify our research in two dimensions - 1) research with intimate body material and 2) research with personal care wearable devices. Both of these dimensions involved female participants in gathering quantitative and qualitative data.

The research with body materials includes intravenous and menstrual blood, data collection, experimentation and evaluation. The process of collection, methods of investigation and handling of the fluid described in this thesis can be used as a template with other bodily fluids such as urine, vaginal discharge etc. For example, researchers can follow the same experimental methods of designing a curved surface for orientation and fluid-dropping location to understand the effect of body variations. Similarly, a researcher can follow the survey's methodology, gathering participants and how to collect, store and dispose of intimate body fluid while working with biological materials. Recent bio-material advancements open new scope for sustainable design, affordable healthcare, personal informatics and diagnostics. Personal bio-chips with programmable microfluidic can replicate the lab reaction to at-home testing [157], creating new opportunities for female diagnostic devices where microfluidics can be used to analyse menstrual blood.

Beyond these, the challenges highlighted in this thesis open up the scope for new interventions, such as designing new manufacturing methods and machines for sanitary napkins, low-cost soft-hard connectors designed for easy attachment, better conductive thread etc. The

system design process can be followed for designing new personal care systems for monitoring or diagnostic purposes, such as smart innerwear, intelligent diapers [158] etc. The idea of resistance change with the fluid volume may be applied in other forms in the clinical industry, for instance, measuring blood loss during surgery or monitoring postpartum blood loss [159]. The investigation should also extend to other forms, such as wound recovery detection, where volume measurement is not essential. Still, the detection of blood is vital for identifying whether the wound is healing or not. Moreover, by adding other material or sensing capabilities for identifying bacteria and fungus, a smart bandage [160] can be made to notify users and practitioners of wound healing progress.

The burgeoning use of technologies in personal health informatics can inform users of their health status privately. The recent pandemic has grown online health consultation into a general practice allowing social distancing and the safety of patients and practitioners. Users can privately collect data, access it on-demand, analyse and share it with the practitioners when required. This will allow more privacy and agency for the women. The clinicians can check, explore and create proper medication based on the data remotely. Difficulties understanding the effect of medicines on irregular menstrual volume were challenging due to subjective estimation methods. Our research would enable clinicians with objective information on menstrual volume and proper medication management. Using artificial intelligence to inform users about their menstrual health conditions and suggest a visit to gynaecologists is a potential application of our system that tool designers and product designers can explore.

Besides these, menstrual health social workers, Non-Governmental Organisations (NGOs) face challenges in menstrual education, communication, privacy, and literacy due to the shame and taboos associated with menstruation. Our research can support them by setting the stage for private monitoring of menstrual health information that would minimise the communication challenges wherever group communications are needed, for example, remote medication and consultation in rural areas on menstrual health.

Additionally, it is kind of urgent that the HCI community focus on inexpensive and easy-to-adopt remote design ideas to empower low-literate and women populations in society to

avoid their relegation further. Investing in ubiquitous technologies becomes apparent in the current time of the COVID-19 pandemic. With the varying educational status of females, it is insufficient to bring technologies to use; females should be empowered to adopt them over time. Understanding the role of other cultural and ecological factors that might shape the use of technological interventions is essential. While the rest of the world is moving forward by adopting new tools for online working modes, women with low digital literacy and resource constraints face a dearth of tools and a communication gap. Our platform provides a case in favour of this need for women.

Chapter 7

Future Work & Conclusions

This thesis aims to advance our understanding of why and how to design a sanitary napkin sensor for bodily fluid volume monitoring using conductive textiles. To this end, we first outlined the design process of the sanitary napkin sensor, starting from gathering information through a survey and identifying the problems, the design of the sensor with benchtop experiments to evaluate the design (Chapter 3). Subsequently, we characterized the factors impacting the sensor data with user studies (Chapter 4). In this chapter, we restate the thesis statement, research questions, and contributions, then generalize from the research presented here by proposing guidelines for future investigation and identifying open challenges and opportunities for future research. We then discuss this research from various other perspectives to connect the outcomes of this research to the broader field and its potential importance. Finally, we conclude with a summary of this thesis.

7.1 Restatement of the Thesis Statement, Research Questions and Contributions

My thesis statement is as follows:

A sanitary napkin for women can help in monitoring of the bodily fluid loss volume.

In this thesis, we considered the following two research questions.

- **RQ1** Can a sanitary napkin sensor be designed to measure the menstrual blood loss volume? (Chapter 3) 35
- **RQ2** What effect do the activities performed by the user have on a minimally invasive, wearable sanitary napkin system built for the measurement of bodily fluid? (Chapter 4)

7.2 Contributions

As a direct consequence of answering these questions, we made the following contributions to the space of menstrual health monitoring system research.

- Design and evaluation of an absorbed blood volume sensor with a resolution of 0.5 mL embedded in an off-the-shelf sanitary napkin.
- Investigation of different sensor parameters such as proper spacing to detect the output, effect of orientation and weight on the sensor.
- A model for prediction of intravenous blood volume from the output voltage created using blood data of 18 participants.
- A model for the prediction of menstrual blood volume from the output voltage was created using 40 menstrual blood data collected from 10 participants.
- Design of a wearable sanitary napkin system that helps to monitor the effect of different activities performed by the user.
- Insights collected from the in-the-wild study with saline for different activity on the sensor for all users.

7.3 Critical Reflection

Before we list our ideas for future work in the next section, we take a moment to reflect on our work presented thus far. We have identified and discussed below the criticism of our work and provided our ideas for addressing the concerns in future work.

7.3.1 Restricted Data Collection

In the last two chapters, we discussed the challenges and issues of data collection and limited user availability. We observed during the study that women felt uncomfortable and were reluctant to take part in the study. For users' comfort and availability, we collected data only during the daytime during office hours. However, since the fluid volume and composition change for every user with days of the menstrual cycle, it is difficult to say the effect of blood property change on the sensor. Upon reflection, we acknowledge the limitation of the data collection, which could be addressed with future investigations. One way to collect more data from each user is to recruit participants for the complete menstrual cycle. This may be possible in a clinical setting for complete data collection.

7.3.2 Characterizing Complex Activities In a Day

We have characterized four basic activities in this thesis and assumed other activities as a combination of these four activities standing, sitting, walking and lying down. However, the frictional forces change while performing other activities. For example, we have considered running as a combination of standing and walking however the lateral force applied on the napkin while running may be more than walking and standing. We realized more activities will increase the complexities of the analysis as well as the characterization and gathering of participants would be difficult hence, we started with a reasonable number of activities for the specified amount of time.

Despite our concern about increasing the activities for a day, we have thought of several

ways to improve the sensor design and conduct study in subsequent research. Firstly conducting user studies at different times of the day with different users depending on the activities they perform. Also, giving control of the data collection to the users. For example, users who work most of the time sitting and users who are generally more active during the day can be divided and data collected during the day and night. This will allow gathering different activity data of each person such as sitting and lying down or walking and lying down. Also giving control of data collection will help users to collect the data only for the specified activity. For instance, if sitting data is required from a user who works sitting mostly during the day, can switch off the data collection when the user is moving for a while.

7.4 Open Challenges & Opportunities for Future Research

Many challenges and opportunities remain for developing our understanding of how the fluid composition effect, how it changes with days and what modifications can be made to make the design more effective for the users. While the full coverage of a broad space of these open-ended questions represents is left to the future researchers, here, we will initiate the process by analysing the assumption that we implicitly make in order to insinuate the alternative paths. We also discuss some initial explorations we made in these future directions.

7.4.1 In-The-Wild Study With Menstruating Users

In-the-wild studies with menstruating users can be one of the very prominent next steps for future research. We have identified challenges and opportunities for research in this direction. The first step is to design the system in such a way that the user can control the data collection. Safety, comfort and reliability are the major concerns to take care of. Since the knowledge base of the users may vary, hence the system should be easy to use.

Another hurdle is the variation in the menstrual flow and composition. Since there is no system to measure the blood flow during menstruation from the user's body, ground truth data

collection is not possible. Moreover, the impact of the variation in menstrual fluid properties is also unknown. Therefore, the characterization of these parameters is necessary for evaluation. To start with this, our characterization of the effect of activities on the users is the first step in this research direction.

7.4.2 Fluid Property Variation

The menstrual fluid property and flow change with days of menstruation for each user. Also, the fluid composition is not the same for all users. Moreover, the composition of menstrual blood [161,162] and how it varies with time have not been explored in many research. Therefore, understanding and investigating the variation in the fluid could be a way of expanding this research. One direction to start with is to collect and segregate menstrual blood samples based on time for each user and conduct experiments on benchtop settings.

7.4.3 Alternative Design Considerations

We designed this wearable system to collect continuous data for a specified time. Our foremost concerns were the comfort and safety of the users. However, during the data collection process and user studies, we observed that participants were more concerned about their work and tended to forget things about the data collection if not reminded. This is human nature that two tasks can not be given equal importance at the same time [163-165]. Thus minimizing user interruption as much as possible would make the wearable system more convenient to use. Removing the battery helps to reduce the hassle of charging. Near Field Communication (NFC) technology can be used to power the system for data collection and communication.

7.4.3.1 Sustainable Design

Another critical dimension to consider is how to make the sensing system design more sustainable. In this research, we reused the electronic wires and modules after sanitation and sterilization to minimize the e-waste. However, for the in-the-wild study with users, it may not

be possible to reuse it by themselves. Further research can focus on making this wearable sanitary napkin system environment-friendly considering the sustainable development goals [166]. For instance, the sanitary napkin sensor can be made with cotton-based materials and washable conductive thread. Conductive fabric connectors can replace the wires. The system can reuse electronic circuits.

7.4.3.2 Alternative Methods of Design

We chose the iterative design method; however, a participatory design could be another exciting method one could follow in this kind of design process. The design method can involve stakeholders such as sanitary napkin manufacturers, users, clinicians and social workers, non-governmental organisations, and researchers. This design method needs to address the challenges in these settings, such as the knowledge gap between the stakeholders. For example, the social workers or the users may not be aware of the sanitary napkin manufacturing process and its limitations, and clinicians may not know the difficulties of creating hard and soft connectors. One way to address the communication gap is through dialogue-based interactions with individual stakeholders, gathering the design requirements and ideas for development.

Conclusions

In this thesis, we demonstrate the design and development of a textile-based sanitary napkin sensor to monitor menstrual blood loss and characterise the effect of various activities performed by the user on the sensor. The sanitary napkin sensor is flexible and extensible to many wearable applications such as sweat rate, urine, and blood loss. We also investigated the effect of body weight, orientation, and location of fluid drop on the sensor. We evaluated these parameters with saline, human blood and menstrual blood on a benchtop setting. Two regression models created with the data collected from 18 and 10 participants for intravenous and menstrual blood respectively work well for predicting the volume values. We redesigned and extended the work to investigate the effect of users' activities through user studies. The results show

consistency in the sensor's output across activities. The insights gathered from these studies can be extended to various other application areas such as smart diapers, imaginative costume designs, and conducting investigations in those areas. Also, this sensor can be used for further enhancement in the field of healthcare.

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Publications

Journals

- J1. Manideepa Mukherjee, Sana Ali Naqvi, Anushika Verma, Debarka Sengupta, Aman Parnami “MenstruLoss: Sensor For Measuring Menstrual Blood Loss,” submitted in *PACM on Interactive, Mobile, Wearable Ubiquitous Technologies*, vol 3, 2019.

Workshop

- J1. Manideepa Mukherjee, “Challenges and Opportunities of Textile Based Smart Sanitary Napkin Design ” submitted in *Adjunct Proceedings of the 2019 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2019 ACM International Symposium on Wearable Computers*, 1044-1046, 2019.

Appendix A

Matlab Code

Listing A.1: Matlab Code for ML

```
total=18;
no_training=floor(total*0.8);
no_testing=floor(total-no_training);
p = randperm(total);
p = p(1:total);

inputMatrix=RegressionData;
predictors = [];
response = [];
for i= 1:no_training
    response = [response;inputMatrix(:,1)];
    predictors = [predictors;inputMatrix(:,p(i)+1)];
end

predictors_testing = [];
```

```

response_testing = [];

for i= no_training+1:total
    response_testing = [response_testing;inputMatrix(:,1)];
    predictors_testing = [predictors_testing;inputMatrix(:,p(i)+1)];
end

inputTable=[response ,predictors ];
testTable=[response_testing ,predictors_testing ];

% Train a regression model
% This code specifies all the model options and trains the model.
regressionGP = fitrgp (...
    predictors , ...
    response , ...
    'BasisFunction' , 'constant' , ...
    'KernelFunction' , 'matern52' , ...
    'Standardize' , true);

regressionGP_exp = fitrgp (...
    predictors , ...
    response , ...
    'BasisFunction' , 'constant' , ...
    'KernelFunction' , 'exponential' , ...
    'Standardize' , true);

responseScale = iqr(response);
if ~isfinite(responseScale) || responseScale == 0.0

```

```

    responseScale = 1.0;
end
boxConstraint = responseScale/1.349;
epsilon = responseScale/13.49;
regressionSVM = fitrsvm (...
    predictors , ...
    response , ...
    'KernelFunction' , 'gaussian' , ...
    'PolynomialOrder' , [], ...
    'KernelScale' , 0.25 , ...
    'BoxConstraint' , boxConstraint , ...
    'Epsilon' , epsilon , ...
    'Standardize' , true);

regressionTree = fitrtree (...
    predictors , ...
    response , ...
    'MinLeafSize' , 4 , ...
    'Surrogate' , 'off');

responseScale2 = iqr(response);
if ~isfinite(responseScale2) || responseScale2 == 0.0
    responseScale2 = 1.0;
end
boxConstraint2 = responseScale2/1.349;
epsilon = responseScale2/13.49;
regressionSVM_Cub = fitrsvm (...
    predictors , ...

```

```

response , ...
'KernelFunction' , 'polynomial' , ...
'PolynomialOrder' , 3 , ...
'KernelScale' , 'auto' , ...
'BoxConstraint' , boxConstraint2 , ...
'Epsilon' , epsilon , ...
'Standardize' , true);

a = bootstrp(1000,@(boot) std_predict(regressionGP , boot),inputTable);
b = bootstrp(1000,@(boot) std_predict(regressionGP_exp , boot),inputTable);
c = bootstrp(1000,@(boot) std_predict(regressionSVM , boot),inputTable);
d = bootstrp(1000,@(boot) std_predict(regressionTree , boot),inputTable);
%e = bootstrp(1000,@(boot) std_predict(regressionSVM_Cub , boot),inputTable);

%disp(z);

figure();
boxplot([a, b ,c ,d]...
, 'Labels' ,{'M1' , 'M2' , 'M3' , 'M4'} , 'notch' , 'on');
disp('done');
ylabel('Residual_Error' , 'FontSize' ,10 , 'FontName' , 'Times_New_Roman');
set(gca , 'FontSize' ,10 , 'FontName' , 'Times_New_Roman');

```

Listing A.2: Matlab Code for MAPE calculation

```

function std= for_calc_mape(model , data)
x=data(1,1);%vol

```

```

y=data(1,2);%vout
p=predict(model, y);
diff=abs((p-x)/x);
std=diff;
y_GT=x;
y_pred=p;
end

```

Listing A.3: Matlab Code for Ploting

```

function [std,y_GT,y_pred,y]= for_plot(model,data)
x=data(1,1);%vol
y=data(1,2);%vout
p=predict(model, y);
diff=abs(p-x);
std=diff;
y_GT=x;
y_pred=p;
end

```

Appendix B

Microcontroller code

Listing B.1: Teensy Microcontroller Code

```
#include <Wire.h>
//#include <SmeNfc.h>
#include <Arduino.h>
#include <SPI.h>
// #include "RTCLib.h"
#include <SD.h>
#include <Servo.h>

Servo s;
File myFile;

int block=0;
float voltage=0;
int chk = 1;
const int PIN_LED_13 = 13 ;
float Vout=0, R2=0, volume = 0;
```

```

String sd_data;

// RTC_DS1307 rtc;
// String day, hour, minute, seconds, timestamp, filename;
String filename, timestamp;
// int f_hour, ff=0;

long s_time_disp=0, c_time_disp=0, s_time_data=0, c_time_data=0, exp_start=0;

char file [12];

void setup () {

    pinMode(PIN_LED_13, OUTPUT);
    pinMode(20, OUTPUT);
    pinMode(21, OUTPUT);
    pinMode(22, OUTPUT);
    pinMode(23, OUTPUT);
    //Initialize the SmartEverything as Master
    Wire.begin ();
    pinMode(2, INPUT);
    //initialize USB console
    Serial.begin(9600);

    randomSeed(6);

//    time_update ();

```

```

// filename = String( hour + minute + "-" + day + ".txt");
filename = String("exp.txt");
Serial.println(sizeof(filename));

filename.toCharArray(file , sizeof(filename));

// File initiation
if (!SD.begin(10)) {
    Serial.println("initialization_failed!");
    while (1);
}
Serial.println("initialization_done.");
// String f = filename;

myFile = SD.open(file , FILE_WRITE);
if (myFile) {
    Serial.print("Writing_to_");
    Serial.print(file);
    // myFile.println("This is a test file :)");

    myFile.close();
    //Serial.println("done.");
}
else {
    Serial.println("error_opening_test.txt");
}
// File initiation end.

```

```

delay(10000);

exp_start = millis();

s_time_disp = exp_start;
s_time_data = s_time_disp;

delay(1);

exp_run();

}

void wait_seconds(int sec)
{
    delay(sec * 1000);
}

void wait_minutes(int minute)
{
    delay(minute * 60 * 1000);
}

void data_read()
{

    if (chk){
        block = check();
    }
}

```

```

}

if(block==1){
chk=0;
Vout = block_1 ();
}

else if(block==2){
chk=0;
Vout = block_2 ();
}

else if(block==3){
chk=0;
Vout = block_3 ();
}

// time_update ();

// timestamp = String("H" + hour + "M" + minute + "S" + seconds);
timestamp = String("HOMOSO");

String rs = String(R2);
String vs = String(Vout);
String Vol = String(volume);
String blk = String(block);

```

```

sd_data = String(timestamp + "V" + Vol + "R" + rs + "Z" + vs + "B" + blk);
Serial.println(sd_data);
data_card();

delay(10);

}

```

```

//void exp_run()
//{
//
//  dispense(0.5);
//
//  long curr_exp = millis();
//
//  while(curr_exp - exp_start < (15)*60*1000) // run for 15 Minute
/////  while(curr_exp - exp_start < 7400000) //
//  {
//    curr_exp = millis();
//    c_time_disp = curr_exp;
//    c_time_data = c_time_disp;
//
//    if(c_time_disp - s_time_disp > (60)*1000) // drop every 60 sec
//    {
//      s_time_disp = millis();
//      dispense(0.5);
//    }

```

```

//
//   if(c_time_data - s_time_data > (5)*1000) // every 5 sec
////   if(c_time_data - s_time_data > 60000)
//   {
//     s_time_data = millis();
//     data_read();
//   }
// }
//}
void exp_run()
{
    for (int i=0; i<13;i++)
    {
        dispense(0.5);

        wait_seconds(20);

        data_read();
    }
}

int volume_update(float v)
{

    // if (volume == 6.4) return 0;
    volume += v;
}

```

```

// void time_update()
// {
//     int h=0,m=0,s=0,d=0;

//     DateTime now = rtc.now();

//     if(ff)
//     {
//         f_hour = now.hour();
//         ff=0;
//     }

//     h = now.hour();
//     m = now.minute();
//     s = now.second();
//     d = now.day();
//     if (f_hour>0 && h==0) h += 24;

//     day = String(d);
//     hour = String(h);
//     minute = String(m);
//     seconds = String(s);

//     if (h<10) hour = String("0"+hour);
//     if (m<10) minute = String("0"+minute);
//     if (s<10) seconds = String("0"+seconds);

```

```

//  if (d<10) day = String("0"+day);
// }

void data_card()
{
  // Serial.println("In function");
  myFile = SD.open(file , FILE_WRITE);
  if (myFile) {
    Serial.print("Writing the data to ");
    Serial.println(file);
    myFile.println(sd_data);

    myFile.close();

    for(int x=0; x<3;x++)
    {
      digitalWrite(PIN_LED_13, HIGH); // turn the LED Off
      delay(100);
      digitalWrite(PIN_LED_13, LOW);  // turn the LED on
      delay(100);
    }
  }
}

void dispense(float v)
{

```

```

volume_update(v);

// Serial.print("@");
Serial.println("\nservo_on");
  for (int i = 0; i < 5; i++)
  {
    s.attach(9);
    delay(50);
    s.write(180);

    delay(350); // change time acc. to volume
                //350 for 0.1 ml

    s.write(90);
    delay(50);
    s.detach();

    delay(250);
  }

  Serial.println("\nservo_off");

// wait_seconds(3.1); // 30s delayy for immediate data

// data_read();

}

```

```

void loop()
{

    digitalWrite(PIN_LED_13, LOW); // turn the LED Off
    delay(100);

    digitalWrite(PIN_LED_13, HIGH); // turn the LED on
    delay(100);

}

```

```

int check(){

    float vol;
    for(int j=1;j<=3;j++){
    switch(j){
        case 1:
            vol = block_1();
            break;
        case 2:
            vol = block_2();
            break;
        case 3:
            vol = block_3();
            break;
    }
}

```

```

if (vol>0.2){
    Serial.print("\nBlock_");
    Serial.print(j);
    Serial.print("_selected\n");

    return(j);
}
    // rnpn transistor as eturn(0);
}
return(0);
}
float block_1(){

    digitalWrite(20, HIGH);
    digitalWrite(21, LOW);
    digitalWrite(22, HIGH);
    digitalWrite(23, HIGH);

    delay(50);

    float sum_v=0, sum_r=0, R1=5600, buffer1=0, voltage=0;

    for (int i = 0; i < 10; i++)
    {
        int raw_v = analogRead(0);

```

```

buffer1 = raw_v * (3.3);

voltage = (buffer1) / 1024;
buffer1 = (3.3 / voltage) - 1;
R2 = R1 * buffer1;

sum_v += voltage;
sum_r += R2;

if(!chk){
delay(970);}

}

voltage = sum_v/10;
R2 = sum_r/10;

Serial.print("Block_1_Vol_—>");
Serial.println(voltage);
Serial.println("\n\n");

return(voltage);

}

float block_2(){

digitalWrite(20, LOW);

```

```

digitalWrite(21, HIGH);
digitalWrite(22, HIGH);
digitalWrite(23, HIGH);

delay(50);

float sum_v=0, sum_r=0, R1=5600, buffer1=0, voltage=0;

for (int i = 0; i < 10; i++)
{
    int raw_v = analogRead(1);

    buffer1 = raw_v * (3.3);

    voltage = (buffer1) / 1024;
    buffer1 = (3.3 / voltage) - 1;
    R2 = R1 * buffer1;

    sum_v += voltage;
    sum_r += R2;

    if(!chk){
        delay(970);}

}

voltage = sum_v/10;
R2 = sum_r/10;

```

```

Serial.print("Block_2_Vol_—>");
Serial.println(voltage);
Serial.println("\n\n");

return(voltage);

}

float block_3(){

digitalWrite(20, HIGH);
digitalWrite(21, HIGH);
digitalWrite(22, HIGH);
digitalWrite(23, LOW);

delay(50);

float sum_v=0, sum_r=0, R1=5600, buffer1=0, voltage=0;

for (int i = 0; i < 10; i++)
{
    int raw_v = analogRead(2);

buffer1 = raw_v * (3.3);

voltage = (buffer1) / 1024;
buffer1 = (3.3 / voltage) - 1;

```

```
R2 = R1 * buffer1;

sum_v += voltage;
sum_r += R2;

if (!chk){
delay(970);}

}

voltage = sum_v/10;
R2 = sum_r/10;

Serial.print("Block 3_Vol->");
Serial.println(voltage);
Serial.println("\n\n");

return(voltage);

}
```