Monitoring Congestive Heart Failure using Pressure-Sensitive Mats

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Abstract — Heart failure affects 22 million people worldwide. Current diagnosis techniques are based on a combination of medical history and physical examination performed by a physician. Non-invasive continuous monitoring of patient health and physiology are part of a growing research field. Pressure sensitive mats have been used to estimate force, analyze bed transfers, and monitor breathing patterns during sleep. This paper describes the application of pressure sensitive mats to identify small changes in mass distribution (~1% of body mass) as a model of fluid retention that occurs with congestive heart failure (CHF). This paper employs a recently developed anthropometric model to demonstrate that the addition of a 100g mass at the ankle, shin, knee, thigh, and bladder regions were detectable under ideal conditions. A number of confounding factors that may influence real-work measurements are discussed. Although preliminary, these findings suggest that pressure sensitive mats may form the basis for a novel non-invasive system to assist physicians in monitoring CHF by tracking associated fluid retention and redistribution over the course of a night.

I. INTRODUCTION

Heart disease is one of the two leading causes of death in men and women in Canada accounting for half of all deaths\textsuperscript{[1]}. There are 1.3 million people in Canada (22 million worldwide) who are living with heart disease. This leads to over 305,000 hospitalizations costing the Canadian economy about $30 billion annually \textsuperscript{[2]}\textsuperscript{[1]}.

One form of heart disease is heart failure (HF). HF results from the heart being unable to sustain the necessary blood flow throughout the body due to damage to the heart tissue or other causes \textsuperscript{[3]}. The heart may compensate for the lack of flow by increasing its workload to account for the decrease in blood pressure in order to pump blood throughout the body. This increase can lead to heart palpitations and an increased heart rate (HR). The most common causes of HF are ischemic heart disease, hypertension and diabetes \textsuperscript{[4]}. This can cause difficulty in breathing, lower extremity edema, fatigue, nausea and lack of appetite \textsuperscript{[4]}.

Reduction of the heart pump effectiveness (HF) leads to reduced kidney perfusion and kidney function and hence fluid overload. Fluid often accumulates in the feet and ankles and also around the lungs causing difficulties breathing \textsuperscript{[3]}. This form of HF is known as congestive heart failure (CHF) and is prevalent in older adults.

The current method of CHF diagnosis is based on thorough medical history and physical exam along with a variety of diagnostic tests to determine the severity \textsuperscript{[3]}. In hospital settings physicians may order daily weighing to determine fluid status. Current treatment often involves pharmacological therapies and may include the use of a biventricular pacing device to synchronize ventricular activation in order to improve cardiac output \textsuperscript{[3]}\textsuperscript{[5]}.

A new area of medical diagnosis and monitoring is non-invasive technologies. This new area has the potential to replace current and more invasive technologies. Additionally, many diagnostic methods rely on data acquired while a person is in a hospital and/or continuing care facility. The application of continuous non-invasive monitoring technology in a person’s home may help in the identification and monitoring of disease \textsuperscript{[6]–[8]}. Furthermore, at-home monitoring can potentially reduce the strain on the health care system and maintaining an aging persons independence \textsuperscript{[9]}.

Fannucci et al have proposed a smart home monitoring system to track the vital signs of CHF patient. The system collects vital signs and sends them to the Hospital Information System to be evaluated by physicians \textsuperscript{[8]}. Vital signs included electrocardiogram, SpO2, blood pressure, and weight \textsuperscript{[8]}. This system aims to reduce the number of in-person visits needed by each patient, while maintaining the necessary health tracking associated with individuals with CHF \textsuperscript{[8]}. While this system represents an important progress towards home monitoring of patients with CHF, it requires active patient compliance. Furthermore, a non-contact solution would be preferable.

Clark et al. proposed a telehealth framework for monitoring CHF patients at home \textsuperscript{[10]}. The system made use of digital scales, which wirelessly communicated the patient’s daily weight to a heart failure clinic via computer or fax. This monitoring framework has been shown to help with patient outcomes \textsuperscript{[10]}. However this technology again relies on patient compliance and is affected by external factors such as clothing.

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The use of pressure sensors in monitoring a person while sleeping is a growing area of research. Pressure sensors may be arranged in an array within a mat and placed between a person’s mattress and bed frame. It has been identified that these arrays can be used to detect breathing patterns (sleep disordered breathing) [11], [12], posture recognition [13]–[16], prevention of pressure ulcers in bed-bound patients [17], and bed entrance and exits [18]–[22]. The estimation of force from pressure sensors has also been investigated [23] using pressure sensors.

This paper proposes the use of a non-invasive pressure sensor array to monitor small variations and patterns of movement in patient mass, which may be indicative of worsening heart failure. Through continuous monitoring of dynamic mass redistributions over the course of the night, such a system may more effectively identify patients with worsening CHF. Such early detection may trigger less invasive therapies and avoid unnecessary hospitalizations. Specifically, one expects patients suffering from CHF to have significant fluid retention pooled in their ankles and feet by the end of a day due to their upright posture. Over the course of the night, assuming the patient is horizontal, the fluid will begin to redistribute away from the lower extremities, travelling to the middle of the body and resorbed into the circulatory system, ultimately to be filtered by the kidneys and stored in the bladder. By monitoring mass shifts while a patient sleeps over the course of the night, one may detect this change in mass and pattern of mass shift from the lower extremities to the abdomen area.

We have previously demonstrated that a pressure mat can detect static changes in mass in the range of 50-400g in the ankle region using an anthropomorphic human body model [24]. However, the ability to track the redistribution of fluid mass from the ankle to the abdomen has not been investigated, nor has the sensitivity to such small mass changes been evaluated in more massive regions such as the thighs.

Ultimately, to make a practical system for monitoring CHF using pressure-sensitive mats will require addressing several potentially confounding issues. In addition to proposing this novel use for pressure-sensitive mats to monitor CHF, this paper will specifically address question of whether a pressure-sensitive mat has the sensitivity required to detect mass changes typical of fluid retention observed in patients with CHF.

II. MEASUREMENT SYSTEM

The measurement system included a previously validated 2D and 3D Anthropometric Human Body Model placed directly on three pressure mats (S4 Sensors Inc.) [24]. The model was created based on anthropometric measurement of an older female adult (70 yrs., 1.59 m and 71 kg). The pressure mats are each 80x25cm containing 24 equally spaced (10x10cm) fiber optic emitter-sensor pairs. Foam surrounds each emitter-sensor pair. When pressure is applied to the mat this foam is compressed, altering the alignment of emitter-detector pairs and moderating the amount of light detected by the sensor. This change in detected light is converted to a unitless pressure response. Data from all 72 sensors are recorded a rate of 20Hz and saved as a CSV file for each session.

III. TESTING

A two minute calibration session was recorded initially with only the 2D model placed on the mats (Figure 1). The 3D model was then placed directly on the 2D model with each body segment aligned to its equivalent 2D outline and data were recorded for a period of two minutes. To model fluid retention experienced by CHF patients, a 400g bag of hydrated potassium acrylate (AgSAP, 800-150um dry) crystals (M2Polymer, West Dundee, IL) was used. This mass was chosen as it reflects an amount of fluid retention that would start to be clinically relevant in CHF patients (<1% of total model mass). Five 2-minute data sessions were recorded with the addition of the AgSAP 400g bag placed at the left ankle, shin, knee, thigh, and bladder region. This resulted in seven CSV files in total. This method was repeated using progressively lower weighs. Our results indicate that, for the sensors used in this study, 100g was the lowest reliably detectable weight at all measured locations.

All calibration and temporal filtering (averaging over the two minute sample) was completed in MATLAB. Each file representing the addition of weight to the aforementioned body regions were then compared to when the model was directly on the mat without additional mass. The resulting pressure measurements were plotted in Figure 2 (400g) and Figure 3 (100g) using a heatmap where higher pressures are indicated using hotter colours (e.g. yellow).

IV. DISCUSSION

As can be seen in Figure 2 and 3, the 400g and 100g masses respectively are clearly detectable at all positions. Considering that the thigh and abdomen regions are
significantly more massive than the ankles, it was not clear \textit{a priori} whether such a small percent change in mass would be discernable by the pressure sensitive mat. Therefore, it appears possible to track a minimum of 100g addition from the ankle to the bladder region. Under ideal conditions, a calibration session was collected and accurate identification of when/where the addition of mass was applied was also achieved.

While this result is promising, testing performed in this study was done under ideal conditions. Here, an anthropometric model was used under static conditions rather than a true dynamic human subject. Therefore potentially confounding pressure changes were ignored, such as from breathing or body movement. In order to use this method of mass distribution tracking in a smart home setting, possible confounding factors must be identified and addressed. The following sections outline some potential confounding factors together with a discussion of how each might be addressed. Future work will address each confounding factor to achieve a deployable solution.

\textbf{A. Patient movement}

In a real world setting pressure sensitive mat data would be recorded continuously throughout the night. Dynamic movement experienced during some stages of sleep will influence the pressure response and may lead false indications of mass change [15, 16]. Identification of periods of movement and rest will permit the analysis of mass change only during periods where the patient is still.

\textbf{B. Patient posture}

Patient posture during data recording must also be accounted for. Work conducted in our lab has previously demonstrated that it is possible to detect patient posture under static conditions [13]. The problem becomes more complex when dynamic conditions are introduced (e.g. restless sleep). Therefore, dynamic movement analysis is an area of future research.

The pressure mats do not directly measure a patient’s mass, but give a pressure representation of this mass. This means that, based on the sensitivity of the sensors used and the relative location of the mass applied, multiple pressure values can be observed based on the same applied mass. This phenomenon may occur when an individual is lying in a supine position vs. when they are sitting up. Their mass remains consistent, but the pressure response will appear larger while sitting due to the mass transfer from the upper body. Therefore a posture identification system is needed in order to identify when an individual is either prone or supine for an accurate comparison. Foubert \textit{et al.} have developed a posture recognition system using pressure sensors that provided a 80-90\% detection accuracy for eight distinct postures [13]. Adaptation of their classification system may be able to account for this confounding factor when tracking mass distribution changes.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{MODEL ALONE (A), MODEL WITH 400G ADDED MASS (B) AND PRESSURE DIFFERENCE (C) FOR ADDED MASS AT THE BLADDER REGION (1), THIGH (2), KNEE (3), SHIN (4) AND ANKLE (5)}
\end{figure}
C. Partial coverage of pressure-sensitive mat

Currently the pressure mats do not cover the entire mattress. Therefore, errors may be introduced when a person’s mass is not entirely applied to the pressure mat [23]. When only part of the total body mass is applied to the pressure mat, false changes in mass may be identified. Shifting of mass while only partially on the pressure sensors may be falsely identified as a change in mass distribution. Using larger mats that cover the entire bed surface will help address this potential confounding factor.

D. Sensor drift and spatial resolution

It has been previously identified that fiber optic pressure sensors used in this study may experience significant sensor drift during prolonged application of pressure [23]. Holtzman et al. proposed a method to use pressure sensors embedded in household fixtures in order to estimate force. Four analysis methods were proposed to account for the spatial non-linearities associated with the pressure sensors [23]. It was determined that using an Artificial Neural Network (ANN), trained with model data was the most versatile solution under various conditions [23].

The spacing of the sensors used in the present study can cause differences in observed pressure depending on where the mass is applied relative to the nearest sensor location. The more centered a mass is over a sensor, the higher the measured pressure response, even with constant mass. As pressure-sensitive mat technologies continue to improve, higher resolution and increased sensitivity will improve the system’s ability to accurately identify changes in mass.

E. External changes in mass

Mass changes throughout the night may be an indication of fluid redistribution, but it may be caused by other external factors. One potentially confounding mass change arises from joint inflammation. However, in contrast to retained fluid from heart failure, joint swelling would not be expected to change location during the night. Here, the dynamic movement of mass over the course of the night may be used to distinguish between joint swelling and CHF-related fluid retention.

Monitoring when someone leaves their bed during the night to use the bathroom or consume a snack may be a promising future area of research for CHF as well as other health conditions. The identification of when an individual is entering or leaving their bed [22] and when an individual is in bed for long periods of time [7] has been evaluated. Application of these types of classifiers will provide contextual information for a mass redistribution detection algorithm and may be able to account for false positives due to external mass changes.

Changing bed coverings seasonally or changes in mattresses may be detected during periods where the bed is unoccupied. Presence or absence of spouse or pet is expected to cause relatively large changes in mass that may be easily identified in post processing. This issue becomes more complicated when small changes in mass distributions occur that are not a result of water retention. If a person

![Figure 3. Model alone (A), model with 100g added mass (B) and pressure difference (C) for added mass at the bladder region (1), thigh (2), knee (3), shin (4) and ankle (5)
exits the bed during the night to void their bladder, change clothing, drink water, or eat a snack, a change in patient mass will occur. Clearly, the identification of bed exits and entrances and their distinctions will be important. Current research has indicated that sit-to-stand movement and bed occupancy is detectable using pressure arrays [15], [16], [18]–[20]. Using these methods, identification of increases in pressure after an individual leaves the bed and returns can be correctly labeled as being due to external events.

V. CONCLUSIONS

This paper proposes the use of pressure-sensitive mats to monitor patients with CHF. Experiments applying a realistic mass change (100-400g) to an anthropometric model demonstrated that it is possible to track mass distribution changes throughout the lower body under ideal conditions. The minimum mass reliably detectable at all locations was found to be 100g for the pressure sensitive mats used in this study. A number of confounding factors that must be addressed prior to real world application were identified and discussed. This discussion stressed the importance of tracking the movement of mass over the course of a night, as opposed to single static measurements of mass change. By monitoring mass changes over time, it is hoped that a CHF monitoring system based on pressure sensitive mats may help avoid unnecessary hospitalizations. Continued development of this system will address the confounding factors identified in this study. Future work will also include additional testing using both the anthropometric model and human subjects in more realistic conditions.

REFERENCES


