Pressure Ulcer Prevention through Accelerometer Sensing and Caregiver Notification
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Abstract
In this paper, we describe an accelerometer sensor system to help prevent pressure ulcer development in spinal cord injury patients. Spinal cord injury patients develop pressure ulcers when consistent skin pressure is applied to a bony prominence. Our device monitors patient body position using accelerometer sensors attached to the patient skin, notifying caregivers if the patient remains in the same position long enough to develop an ulcer. We implement a system of three sensors attached to the patient that wirelessly report data to a bedside module. The bedside module calculates the body position using the sensor data in both sitting and laying down positions. Based on notification settings determined by patient caregivers, the bedside module triggers the hospital call button when the patient is at risk of developing an ulcer. The device stores patient position and timing information for reference by physicians through a web user interface. The wireless sensors, bedside module, and information storage system are described and demonstrate the main functionality of the system.

I. INTRODUCTION
A pressure ulcer monitoring device has the potential to dramatically improve the care of spinal cord injury patients [1]. Spinal cord injury (SCI) patients suffer from permanent damage to their nervous systems and must lie in bed or sit in a chair at all times. Because of excessive pressure at the patient’s bony prominences, circulation through the skin can stop locally, gradually creating a pressure ulcer in the tissue [2]. Current methods for treating pressure ulcers are to first prevent ulcer development by relieving skin pressure at regular intervals [3]. If ulcers develop, support surfaces designed to automatically relieve skin pressure are used, though these devices are either ineffective or very expensive [4]. Overall, these existing methods are insufficient in preventing and treating pressure ulcers, as pressure ulcers add an estimated burden of over $1 billion of expenditures to the United States healthcare system each year [5].

The problem of pressure ulcers can be viewed from three different perspectives: the patient, the immediate caregivers, and the physicians. First, the patient’s primary concern is receiving proper care, ideally through prevention of ulcer development. Second, the immediate caregivers treating the patients require any treatment method to be easy to use and maintain. Finally, the physicians monitoring the patients need to customize treatment on a per patient basis, as patients vary in susceptibility to develop ulcers. Moreover, physicians also need accurate records of the patients’ pressure history to make informed treatment decisions.

We present a novel device for assisting caregivers in preventing pressure ulcers from developing. The device continuously monitors the patient’s body posture and automatically detects if a patient is at risk of developing a pressure ulcer. If the patient is at risk, the device notifies caregivers to relieve the pressure on the patient’s skin. Physicians view patient posture history and change patient pressure relief timing settings through a web interface. By helping caregivers both monitor patients and respond to

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patient needs, we can minimize the risk of caregiver failure in preventing pressure ulcer development, ultimately decreasing the number of pressure ulcer cases.

II. BACKGROUND

Physiology of Pressure Ulcers
Because of spinal cord injury (SCI), SCI patients’ blood flows more slowly than in normal people [6]. As a result, SCI patients cannot tolerate excessive skin pressure without loss of blood low. This is particularly significantly at bony prominences, where excessive pressure is most likely to develop [1]. After skin is exposed to prolonged excessive pressure, local skin ischemia will result, followed by pressure ulcers. Pressure ulcers progress by stages, from Stage I to IV with different level of observed skin tissue damage [1].

Current Prevention Methods
The cost for treating pressure ulcers after diagnosis has been enormous. It was estimated by Miller and Delozier [7] that the total cost of treating pressure ulcers was $1.335 billion per year, and a single pressure ulcer can cost anywhere from $2,000 to $40,000 to repair. Preventing pressure ulcers with a low cost method is likely a best medicine.

Standard recommendations for preventing pressure ulcers include regular checkup of body skin tones, regularly changing sleeping or sitting postures to relieve local high pressure, and pressure cushion using pillows or other soft supportings [1]. Based on these recommendations, several medical devices have been proposed to assist caregivers to prevent pressure ulcers. Pressure-reducing bed supports alter the interfacial pressure between the patient and the mattress. Pressure map devices can help identify the local high pressure so that nurses can help relieve pressure on time. Both mechanisms are effective in reducing incidences of pressure ulcers [8]. However, both methods have limited market penetration because they are too expensive for widespread use.

III. DEVICE REQUIREMENTS
A device designed to sense patient posture and alert caregivers as needed can drastically change the landscape of pressure ulcer treatment. At a lower cost than support surfaces, this device would improve caregiver ability to prevent ulcers. Long-term examination of patient posture data provides physicians with more information to understand how the condition occurs. Finally, such a device could be used alongside other prevention methods to further reduce the risk of ulcer development.

Our device aims to assist caregivers in their existing pressure ulcer treatment while also providing doctors with additional information to study the condition. Analyzing the problem from the three perspectives of patient, caregiver, and physician, we derived the following functional requirements:

1. Patient Requirements
   a. Proper Treatment - Prevent pressure ulcers from developing on the patient’s body.
   b. Position Versatility - Usable in both sitting and laying down positions, and can transition between the two seamlessly.
   c. Setting Versatility - Usable for patients in the hospital and patients treated outside the hospital.

2. Caregiver Requirements
   a. Workflow Integration - No additional manual burden for caregivers beyond changing patient’s posture to relieve pressure.
   b. Communication Integration - Interface with existing patient-caregiver communication systems as needed.

3. Physician Requirements
   a. Customized Care - Allow physicians to configure device based on individual patient needs.
   b. Data Collection - Provide accurate reviewable history of patient pressure or posture.
   c. Low Cost - Significantly less expensive than existing support surface or pressure mapping
solutions, allowing for widespread use in preventing pressure ulcers.

**Design Development**

To meet our design goals, we considered three potential strategies. Through basic testing and research, we decided to solve the problem by providing automatic sensing to assist human caregivers. Relying on caregivers to relieve patient skin pressure, the focus of our design is to assist caregivers in relieving the pressure in a timely manner by notifying caregivers when the patient needs to be treated.

With this strategy in mind, we considered various options for sensing ulcer development, concluding that accelerometry is the optimal solution. The low cost, ease of use, and portability of accelerometers led us to choosing accelerometry for our sensing method. Specifically, we detect the patient’s hip angle relative to the surface they are sitting or laying down on, which serves as an adequate proxy for detecting if the patient is at risk of developing a pressure ulcer.

Given our sensing method, we needed a reliable and convenient means to alert caregivers to patient needs. By consulting hospital caregivers, we found that the existing call button system used by SCI patients is the best medium of patient-caregiver communication. To leverage this communication channel, our device exposes a hardware interface that can communicate with a variety of hospital call button systems, alerting caregivers when a patient needs to have their posture changed to relieve pressure.

Finally, we present patient body posture information to physicians through a web interface, usable on computer, tablet, or smartphone devices. According to physicians treating SCI patients, aggregate data of patient posture history provides useful information regarding future treatment procedures. Alongside a list of positions and durations of the patient’s posture history, our device provides a basic data histogram to help physicians understand patient needs.

**System Overview**

![Full system diagram. Three sensors and one wireless transmitter attached to the patient, transmitting to the bedside module. The bedside module connects to the hospital call button and the hospital information server. Physicians can view the information through a web user interface.]

By using accelerometry sensing, interfacing with existing hospital call button systems, and providing an interface for care customization and review, our device addresses the needs of SCI patients, caregivers, and physicians. Our device consists of two main components: a patient care system, consisting of the sensor module and bedside module, and an information aggregation system, consisting of the data aggregation server and the web interface. The full system is shown in Figure 1. Each patient in the hospital has a corresponding patient care device, all of which communicate over the internet with a single information aggregation server for the hospital.

The patient care system is designed to assist nurses taking care of SCI patients. Three 3-axis accelerometers are attached to the patient’s body. Data from the accelerometers are sent wirelessly from the sensors to a bedside module near the patient. Based on the data from accelerometers, the bedside module determines the patient’s body posture and how long the patient has maintained that posture. When a threshold time is reached, the bedside module triggers the call button to alert nurses that the patient’s posture must be changed.

The information aggregation system operates in parallel with the patient devices and is designed
to assist doctors taking care of SCI patients. Data from each bedside station are sent to the central server, which stores data from all the patients in the hospital. Through a web user interface (UI), doctors can view patient posture history, and thus are able to give informed instructions to nurses on customized patient care. Moreover, doctors can configure the specific posture time thresholds for each patient using the web UI.

IV. PATIENT CARE DEVICE
The patient care device has two key modules, the sensor module and the patient bedside module, as shown in Figure 1. The sensor module when attached to a patient’s body is shown in Figure 2.

In the sensor module, we attach three accelerometers to the patient to sense body posture relative to the surface and use an RF transmitter to send data wirelessly to the bedside module. The first accelerometer is placed on the center of the chest to determine whether the patient is sitting or lying down. Based on this sensor’s angle, we adjust the allowed timing interval for a given posture. This section of the module also contains the RF transmitter and button cell battery. The second and third sensors are attached symmetrically on the patient’s hips, connected to the chest compartment via thin wires. From these two sensors, we determine the angle between the patient’s hip and the resting surface. This angle serves as a proxy for determining the risk of developing a pressure ulcer by confirming if skin pressure has been relieved by caregivers recently.

We use the ADXL335 triple axis analog accelerometers produced by Analog Devices to measure static acceleration of gravity when the body is tilted, calculating relevant body posture information in real time. Based on the hip sensors’ symmetrical positioning, a symmetrical reading of gravity from these accelerometers indicates the patient is flat on the surface. Using this known relation as a reference point, we calculate the hip’s angle relative to the surface (example geometry in Figure 3). The bedside module receives the raw sensor data at a rate of one transmission per second and performs the calculations.

The sensor module is battery powered and functions for 10 days without changing the battery. By only enabling the RF transmitter briefly each second to transmit data, we maintain the average current draw of the module at roughly 1mA, low enough to use a CR2032 3V coin cell battery to power the device for 10 days. Future technical improvements detailed in the Future Work section can increase the battery life.

The compartments of the module are attached to the patient’s skin using 3M double sided adhesive for medical applications. To fit patients of different sizes, the existing wires between the
compartments are interchangeable with shorter or longer cables.

**Bedside Module**

Each patient has a single bedside module next to their bed that processes the sensor data. The module receives data from the sensor module through a RF receiver that is keyed to the transmitter on the patient. If the patient has not moved for longer than the allowable amount of time, the module triggers the hospital call button alarm through a hardware interface. The bedside module is connected to the internet and sends patient data to the central hospital server. Figure 4 shows the software control flow of the bedside module.

![Software control flow of the bedside module.](image)

**Fig. 4.** Software control flow of the bedside module. Traverses decision tree each time a sample of data is received from the sensor module, then waits for the next sample.

To ensure the patient is monitored correctly at all times, the bedside module will trigger the hospital call button if no data has been received for over one minute. This ensures caregivers will treat the patient if needed and also indicates that the battery may need to be replaced.

The bedside module in our initial prototype is a Raspberry Pi board. The board is capable of communicating over ethernet, receiving RF data through a USB receiver, and communicating with the hospital call button system through general purpose IO hardware pins.

**V. INFORMATION AGGREGATION SYSTEM**

In order to store patient data, view patient data, and configure individual timing settings for patients, each hospital has a single central server for information aggregation and management. The hospital server and web interface are shown in the full system diagram in Figure 1.

**Information Aggregation Server**

Each bedside module in the hospital communicates with the hospital’s central server. The modules send information about patient posture each time the posture changes, recording the angle of the previous posture, the duration, the start time, and the end time. These data are stored in a patient database for later access by physicians.

The bedside modules receive timing settings for the corresponding patient from the central server. Patients vary in how long they can hold the same posture without risk of developing an ulcer, so physicians customize how long the module should wait before triggering the call button.

**Web User Interface**

Physicians view posture data and configure timing settings for each patient through a web interface (Figure 5). After pointing a web browser at a specific URL, a physician can view how long a patient maintained each position, with the ability to search by date. The physician can also view a real time feed of the patient’s current body angle. In order to give a better understanding of the combined posture data, we present an aggregated histogram of posture history over a specified date interval. Finally, physicians can specify how long a patient can safely be in a given position while laying down or sitting down. These settings are sent through
the central server to the bedside module for use when controlling the call button.

Testing

We measured the accuracy of our sensor module by attaching the sensors to a tripod and recording the angle measured by the sensors at each 10° rotation (setup shown in Figure 6). We considered the readings on the tripod as the actual angle of rotation and the angle read by our sensors as the measured angle. The deviation is calculated by subtracting actual angle from measured angle. The probability density of the deviation is plotted. As shown in Figure 7, the measured angle is within ±3°. Because significant changes in skin pressure occur when hip angle has changed by at least 10°, our measurement system provides satisfactory angle resolution for our purposes.

Alongside sensor accuracy tests, we tested the bedside module control code for both timing accuracy and hospital call button control. We tested the control code with unit tests and patient simulation by placing the sensor module on rotatable objects. In both scenarios, we simulated the call button by lighting an LED, which is electrically equivalent to triggering the hospital call button. We confirmed that the current version of the software accurately triggers the call button when needed, supporting custom time configurations properly.

VI. DISCUSSION

Our device demonstrates potential to reduce the risk of pressure ulcer development in SCI patients from two directions. First, immediate caregivers can more reliably relieve patient skin pressure through call button reminders. Second, physicians can customize patient care based on the patient’s posture history, further reducing the risk of ulcer development. At a total cost of under $200 per patient, our device significantly undercuts the price of existing solutions for pressure ulcer prevention.

Based on our testing, our prototype can track patient posture with enough accuracy to detect if a pressure ulcer may develop. This ensures proper treatment for the patients through call button notifications for caregivers. Since the sensors are attached to the patient’s body, the device works in both sitting and laying down positions as required. The patient care device interfaces with the existing call button system and requires infrequent maintenance, fitting into the caregivers’ current workflow with minimal additional burden.

Our system provides assistance to physicians monitoring SCI patients by keeping an accurate log of patient posture history and enabling per patient customization. By knowing each patient’s posture history, physicians can make informed treatment decisions, potentially detecting that a pressure ulcer may develop before signs emerge on the patient’s skin. This information, coupled with the care customization provided through our system, can greatly reduce long-term risk of ulcer development in every patient.
Overall, our device satisfies almost all of the functional requirements enumerated above. Our prototype system is designed for hospital use only and not for SCI patients in the community, which fails to meet one of our original requirements. Further development can adapt the device for standalone use, as detailed in the Future Work section below.

VII. FUTURE WORK
The prototype reached the level of sophistication required for testing by the West Roxbury Veterans Affairs SCI Center. Testing with real patients is our most important step in future development, but we can make substantial technical and functional improvements to the system as well.

Testing with real patients is necessary to validate the work that has been done and guide future work. We would like to test our device on a limited number of patients to check the device’s function in a hospital, confirm accuracy on an SCI patient, and to validate design choices. Afterwards, we will assess the long term benefit of using our device by comparing a treatment group with the devices to a control group over a longer period of time.

In parallel with small scale testing, we will be pursuing technical improvements to our system. By switching to digital accelerometers in the sensor module and creating a custom circuit board, we can increase the module’s battery life and decrease the module’s size. For long-term scalable deployment, we need a well-engineered information storage server that will use existing database technologies for enterprise caliber storage. We also plan to integrate our system with existing medical record keeping systems for the convenience of the physicians.

We will be developing functional upgrades to create a version of our device for patients in the community. We will first develop an alarm system to alert caregivers outside the hospital that may interface with email, text message, and paging systems. We will then investigate having a larger central server securely handle the data for community systems.

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REFERENCES