Pressure Ulcer Prevention: An Efficient Turning Schedule for Bed-Bound Patients

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***Abstract*—Pressure ulcer is a critical problem for bed-ridden and wheelchair-bound patients, diabetics, and the elderly. Patients need to be regularly repositioned to prevent excessive pressure on a single area of body, which can lead to ulcers. Pressure ulcers are costly to treat and cause many other health problems, including death. The current standard for prevention is to reposition at-risk patients every two hours. This level of attention is becoming increasingly unrealistic for already overworked nursing staff. In this paper, we present a scheduling algorithm that uses data from a pressure mat on the hospital bed to compute a repositioning schedule that minimizes nursing staff interaction while still preventing pressure ulcer formation. Our experimental results show a 30% increase in the average time between repositioning over the standard schedule. Furthermore, some postures were found to be unsafe if not changed for more than one hour.**

I. INTRODUCTION

Soft body tissues are sensitive to prolonged compressive loading, eventually leading to tissue necrosis in the form of pressure ulcers. Pressure ulcers occur more frequently among diabetics, those with spinal cord injuries, patients in medically-induced comas, and other bed-bound patients. Most of these patients either cannot feel pain from lying on the same position for too long, or are unable to move themselves to relieve the pressure. This leads to a sustained compression of tissue, causing impaired interstitial blood flow and localized ischemia that ultimately can result in pressure ulcers [1].

Pressure ulcers severely affect patients' quality of life since the ulcers are painful, difficult to heal, and often extend hospitalization periods. Despite considerable attempts to prevent pressure ulcers, prevalence figures remain unacceptably high. In 2009, the National Center of Health Statistics (NCHS) reported that more than 10% of the nursing home residents had developed a pressure ulcer [2]. According to the Agency for Healthcare Research and Quality (AHRQ), among hospitalizations involving pressure ulcers as a primary diagnosis, about 1 in 25 admissions ended in death [3].

Early detection of any compromised skin area is the first and the most important step in preventing ulcers. The most effective care for a patient with ulcers is the immediate relief of pressure. An established nursing practice is to turn the patient at least every two hours to avoid aggravating the wound. However, the growing nursing shortage and escalating demands on the nursing staff makes it increasingly difficult to provide this level of service [4]. Moreover, a fixed turning schedule is quite inefficient as it doesn't take patients's physiology and clinical history into account.

The contribution of this paper is twofold: first, we propose a system for determining if a patient is at risk for a pressure ulcer based on measurements taken from a pressure mat. Second, an optimization problem is formulated to determine the maximum average interval between posture changes to minimize nursing effort required to prevent pressure ulcer formation.

II. PRESSURE ULCER PREVENTION

Treating pressure ulcers is difficult and costly, making prevention extremely important. Prevention is accomplished by better distribution of body weight across various regions, regular relief of high-pressure areas, and regular skin inspection for early signs of bedsores. Pressure distribution materials include foam wedges, pillows, soft cushions, and air mattresses. The distribution effect tends to decrease quickly due to compression and distortion of the material [5]. Pressure can be actively relieved through manual repositioning of the patients, motorized reconfiguration of the bed, and dynamic pressure redistribution systems. Dynamic cushion systems provide regular pressure relief with preset inflation/deflation cycles. At this time, such systems are not common due to a lack of solid scientific research validating efficacy [6]. Other, more advanced systems with high density sensors and tiled variable-pressure systems are still in R & D phase and far from commercial application [7].

The most common prevention method is still periodic repositioning by the nursing staff. Some patients are at higher risk than others, and therefore should be repositioned and examined more frequently. Risk level is determined by the Braden pressure ulcer risk assessment chart [8]. A nurse fills this chart by entering numbers between 1 to 4 for various risk categories based on a visual inspection of the patient. By nature, this is a limited and subjective measure and fails to address pressure injuries to other muscle and non-skin tissue, referred to as Deep Tissue Injuries (DTI) [9].

Our approach is to come up with an objective measure of patient risk based on pressure experienced by different parts of the body over time. In addition to measuring risk, we propose a method for minimizing the average number of repositionings

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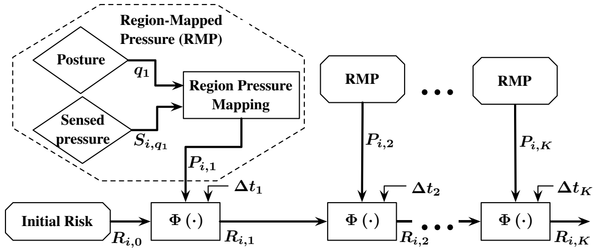

Fig. 1. Risk Accumulation

while keeping the risk of ulcer development within acceptable limits.

III. Pressure Ulcer Risk Assessment

Different parts of the body experience different pressures for the various postures a patient can lie in. Our approach is to track the risk level independently for each at-risk area of the body using a time-pressure risk model. Pressures above a certain minimum pressure, P_{min}, will eventually cause a pressure ulcer, and therefore cause the risk to increase. The amount of increase over time depends on the pressure. Below P_{min}, the risk decreases over time.

Definition 1. (Posture Interval) Given the posture q_k taken from a finite set of postures $\mathcal{Q}$ that starts at time t_k and ends when the patient is repositioned at time t_{k+1}, the posture q_k interval is defined as:

$$\Delta t_k \doteq t_{k+1} - t_k \tag{1}$$

Definition 2. (Risk Accumulating Function) Given the pressure for region i at time t_k, $P_{i,k}$ and the cumulative risk at the end of the previous posture, $R_{i,k-1}$, the new cumulative risk $R_{i,k}$ can be computed using the Risk Accumulating Function (RAF):

$$R_{i,k} = \Phi\left(R_{i,k-1}, P_{i,k}, \Delta t_k\right) \tag{2}$$

An overview of the risk assessment algorithm appears in Figure 1. Each time the patient is repositioned from posture q_{k-1} to posture q_k at time t_k, the pressure $P_{i,k}$ experienced by each at-risk region i of skin is determined using at-risk region pressure mapping. Then, the cumulative risk for each region is determined using the risk accumulating function $\Phi(\cdot)$.

A. At-Risk Regions

Most pressure ulcers form over bony areas of the body such as lower back (sacrum), over the hip bones, heels, back of the head, and even the rims of the ears. Pressure ulcers can also form on the knees, ankles, shoulder blades, elbows, and across the back. Using this information, the body can be divided into a set of N mutually exclusive "at-risk" regions. Only skin areas that are at risk for ulcers in at least one posture are assigned to a region. Figure 2 shows some of at risk regions in different postures according to [10]. More specifically, at-risk regions that we considered in this study are listed in Table I.

B. Region Pressure Mapping

Equation 2 assumes a single pressure, $P_{i,k}$, for each at-risk region. However, the pressure that a region experiences for a single posture can vary across time and space. Furthermore, the piezo-resistive sensors used to measure pressure are arranged in a flat grid on the bed [11].

Definition 3. (Sensor Mapping) For each at-risk region i in posture q_k, $\mathcal{S}_{i,q_k}$ is the set of all pressure sensors touching region i. If region i does not touch the bed for posture q_k, then $\mathcal{S}_{i,q_k} = \emptyset$

Definition 4. (Region-Mapped Pressure) Given $p_s(t)$, the pressure sensed by sensor $s \in \mathcal{S}$ at time t, the region-mapped pressure $P_{i,k}$ is the maximum average pressure sensed by any of the pressure sensors touching region i for the interval Δt_k:

$$P_{i,k} = \max_{s \in \mathcal{S}_{i,q_k}} \left\{ \frac{1}{\Delta t_k} \int_{t_k}^{t_{k+1}} p_s(t)\, dt \right\} \tag{3}$$

The maximum average pressure for the region is a worst-case estimate of the pressure associated with that at-risk region.

C. Time-Pressure Model

As mentioned above, loading a region for too long with a pressure greater than P_{min} will eventually cause a pressure ulcer according to the *Loading Model*. Also, any lower pressure will allow the region to recover according to the *Recovery Model*.

1) Loading Model: Criteria for determining safe levels of pressures and times of exposure, without risk of developing sores, have been established for animals in which pressure sores were artificially produced and for seated humans who were examined for signs of impending pressure sores [12]. Reswick and Rogers demonstrated an inverse relationship between the maximum interface pressure being experienced and the time over which that maximum pressure was applied. Authors in [13] refined this concept and formulated the pressure-time cell death threshold for muscle tissue:

$$P(T) = \frac{P_{max} - P_{min}}{1 + e^{\lambda(T - T_0)}} + P_{min} \tag{4}$$

where the constants of pressure-time injury threshold were chosen in [14] to be $P_{max} = 31\,\text{kPa}$, $P_{min} = 8\,\text{kPa}$, $\lambda = 0.15\,\text{min}^{-1}$, and $T_0 = 95\,\text{min}$.

In order to find the critical time of exposure for a specific amount of pressure, P, we rewrite Equation 4 in terms of time as the function of pressure.

$$T_{max}(P) = \begin{cases} \infty & P < P_{min} \\ 0 & P > P_{max} \\ T_0 + \frac{1}{\lambda} ln\left(\frac{P_{max} - P_{min}}{P - P_{min}} - 1\right) & \text{otherwise} \end{cases} \tag{5}$$

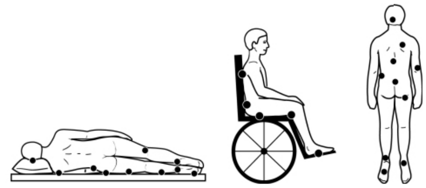

Fig. 2. Most common body sites for pressure ulcers to develop (from [10])

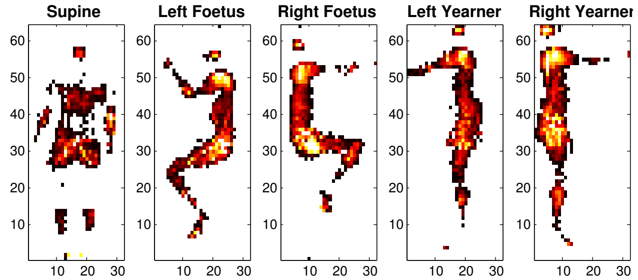

Fig. 3. Pressure mat image of five postures considered in our experimentation

We assume risk increases linearly at a given pressure, and gets values 0 at $T = 0$ and 1 at $T = T_{max}$. Therefore, the risk accumulating function for loading pressures, $\Phi_L(\cdot)$, is

$$\Phi_L\left(R_{i,k-1}, P_{i,k}, \Delta t_k\right) \doteq R_{i,k-1} + \frac{\Delta t_k}{T_{max}(P_{i,k})} \tag{6}$$

2) Recovery Model: When a region is exposed to a safe pressure, $P_{i,k} < P_{min}$, the stressed tissue enters to a phase of recovery. The investigation on the off-loaded recovery interval shows that recovery time increases with load duration and load pressure [15]. Authors in [16] also compared the recovery response of full relief and partial relief. The experimental results of these studies indicate the recovery time is on the order of 15 minutes, which is effectively instantaneous compared to standard repositioning intervals greater than 1 hour. Thus, the risk accumulating function for the recovery model is:

$$\Phi_R\left(R_{i,k-1}, P_{i,k}, \Delta t_k\right) \doteq 0 \tag{7}$$

Note that DTIs may take longer to recover, but this paper is only concerned with the skin-surface pressure sores.

D. Combined Model

Combining (6) and (7), results in:

$$\Phi\left(\cdot\right) \doteq \begin{cases} 0 & \text{if } P_{i,k} < P_{min} \\ R_{i,k-1} + \frac{\Delta t_k}{T_{max}\left(P_{i,k}\right)} & \text{otherwise} \end{cases} \tag{8}$$

IV. A Resource-Efficient Prevention Plan

Pressure sores are painful and slow to heal, but most of them are preventable if good clinical practice is followed. Regular monitoring and repositioning of all of the patients by health care providers are costly especially with the current and expected shortage of nurses. The cost can be minimized for a fixed set of postures by maximizing the average length of time spent in each position. Two cases are considered: a) the hospital has a planned sequence of repositionings, and b) the sequence of repositionings must be determined. In both cases, the optimization goal is to maximize the average repositioning interval while still avoiding high pressure regions.

A. Planned Repositionings

In the case where the full sequence of K repositionings is known, the goal is to choose the time spent in each posture to maximize the average posture interval, subject to the constraint that the risk can never exceed 1. The risk accumulating function is non-linear, but a linear constraint is preferable. It is shown that the following linear optimization problem is equivalent to the original constraint:

$$\text{Maximize} \quad \frac{1}{K}\sum_{k=1}^{K} \Delta t_k \tag{9}$$

$$\text{Subject to} \quad \sum_{k=l}^{m} C_{i,k}\Delta t_k < 1, \qquad \forall\, l, m \in \{1, \ldots, K\}, \quad \forall i \in \{1, \ldots, N\}, \quad l \leq m.$$

$$\text{Where} \quad C_{i,k} = \begin{cases} -\infty & \text{If } P_{i,k} < P_{min} \\ \frac{1}{T_{max}(P_{i,k})} & \text{otherwise} \end{cases} \tag{10}$$

where Δt_k (for every k) is the sole variable iterated to improve the result. In order to show the equivalency, it can be seen that for any sequence of postures such that $P_{i,l-1} < P_{min}$ and $P_{i,k} \geq P_{min} \quad \forall k \in \{l, \ldots, m\}$,

$$R_{i,m} = \sum_{k=l}^{m} \frac{\Delta t_k}{T_{max}(P_{i,k})} = \sum_{k=l}^{m} C_{i,k}\Delta t_k \tag{11}$$

Therefore, our linear constraints guarantee the original constraints of $R_{i,k} < 1$. Now, this problem is a linear programming problem (LP). The program CPLEX is used to solve this optimization [17]. Results are tabulated in Table II.

B. Determining Posture Order

For determining posture order, a greedy algorithm is used: an initial posture is assumed (supine 0°), and the remaining postures are chosen greedily to maximize total time. In this case, no posture is allowed to be repeated, and the sequence has a set length (5 for our experiment). Results are shown in Table III.

V. Experimental Results

To evaluate the validity of proposed scheduling algorithm, the actual pressure data from pressure mat is collected for 3 different subjects lying on a hospital bed. In order to extract pressure mapping model, each subject was positioned in each of 5 different postures as their pressure map images are shown in Figure 3. In the supine posture, pressure data was collected for 0°, 30°, and 60° elevations of the head of the bed.

The collection of at-risk regions in this study for all of the postures is listed in Table I. The postures for which these regions are at risk are listed in the table.

A. Data Collection Platform

A Force-Sensing Array (FSA) [11] was used to collect pressure data from a hospital bed. The FSA system is a flexible mat that contains 2048 (32×64) uniformly distributed sensors that cover the total contact area between the subject and the bed. The FSA system used in this study can measure interface pressure between 0 to 100 mmHg with FSA 4.0 software. The sensor mat is light, thin and flexible and with the sampling frequency of 1.7 Hz.

B. Maximum-Time Turning Schedule

Our scheduling formulation was applied to three subjects in different postures as shown in Figure 3. For each at-risk region, the pressure values obtained from the pressure mat in each posture were used to compute region-mapped pressures. Table II shows the results of our turning scheduling for 5 different postures with fixed ordering for the subjects. In each case, the average interval between turnings is greater than 120 minutes (i.e. the standard practice). It is interesting that the patient in the supine position must be turned in less than an hour. This shows that the standard practice of turning every two hours is not only inefficient, but for some patients may actually exacerbate pressure ulcers because of the loading in certain regions. The greedily chosen sequence of postures shown in Table III improves on the results even further by increasing the average interval. Since, in our pressure model, there is not much overlap in at-risk regions for right and left postures, by considering instantaneous recovery, the maximum time duration is achieved by exchanging between right and left postures.

VI. Conclusion and Future Work

This paper presents a scheduling algorithm to reduce the amount of labor and time required for ulcer prevention by minimizing the number of patient's posture turns that utilizes nursing resources. We used the actual pressure data from the pressure mat on the patient bed to construct our ulcer risk model. Even though in the category of risk factors, pressure is the main contributing factor to the development of pressure ulcers, but there are other elements that can accelerate the formation and progression of pressure ulcer including shear, and skin's temperature and moisture. For more accuracy, physiological parameters of a patient need to be considered. These parameters include nutritional state, blood pressure, disease conditions, age and sex. In our follow up study we intend to use some of these factors in order to generate a more accurate model of ulcer risk for a more realistic scheduling algorithm.

TABLE I
List of at-risk regions

No.	At-Risk Regions	Corresponding Postures
1	back of head	{Supine}
2	right head	{Right Yearner, Right Foetus}
3	left head	{Left Yearner, Left Foetus}
4	right back	{Supine, Right Yearner, Right Foetus}
5	left back	{Supine, Left Yearner, Left Foetus}
6	right shoulder	{Right Yearner, Right Foetus}
7	left shoulder	{Left Yearner, Left Foetus}
8	right elbow	{Supine, Right Yearner, Right Foetus}
9	left elbow	{Supine, Left Yearner, Left Foetus}
10	center sacrum	{Supine}
11	right buttock	{Supine, Right Yearner, Right Foetus}
12	left buttock	{Supine, Left Yearner, Left Foetus}
13	right hip	{Right Yearner, Right Foetus}
14	left hip	{Left Yearner, Left Foetus}
15	right leg	{Supine, Right Yearner, Right Foetus}
16	left leg	{Supine, Left Yearner, Left Foetus}
17	right heel	{Supine}
18	left heel	{Supine}
19	right ankle	{Right Yearner, Right Foetus}
20	left ankle	{Left Yearner, Left Foetus}

TABLE II
Turning Schedule - Predefined Order

	Time Duration (min)					
Sub	1. Right Yearner	2. Supine 0°	3. Left Yearner	4. Right Foetus	5. Supine 30°	Average Interval
# 1	181	62	181	181	52	132
# 2	180	50	180	180	44	129
# 3	212	46	222	232	37	150

TABLE III
Turning Schedule - Greedy Order

Time Duration (min)					
Subject #1					
1. Supine 0°	2. Left Yearner	3. Right Yearner	4. Left Foetus	5. Right Foetus	Average Interval
62	151	181	160	181	147
Subject #2					
1. Supine 0°	2. Left Foetus	3. Right Yearner	4. Left Yearner	5. Right Foetus	Average Interval
74	106	180	180	180	144
Subject #3					
1. Supine 0°	2. Right Yearner	3. Left Yearner	4. Right Foetus	5. Left Foetus	Average Interval
68	177	222	232	181	176

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