A Resource-Efficient Planning for Pressure Ulcer Prevention

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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 extremely costly to treat and may lead to several other health problems, including death. The current standard for prevention is to reposition at-risk patients every 2 h. Even if it is done properly, a fixed schedule is not sufficient to prevent all ulcers. Moreover, it may result in nurses being overworked by turning some patients too frequently. In this paper, we present an algorithm for finding a nurse-effort optimal repositioning schedule that prevents pressure ulcer formation for a finite planning horizon. Our proposed algorithm uses data from a commercial pressure mat assembled on the bed's surface and provides a sequence of next positions and the time of repositioning for each patient.**

***Index Terms*—Constrained shortest path (CSP), posture scheduling, pressure ulcer prevention, resource optimization, tissue stress evaluation.**

I. Introduction

According to the National Pressure Ulcer Advisory Panel [1], a pressure ulcer is defined as a localized injury to the skin and/or underlying tissue usually over a bony prominence, as a result of pressure, or pressure in combination with shear and/or friction. 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 [2].

Pressure ulcers may develop quickly and are difficult to treat. They are painful and can lead to life-threatening complications [3]. Once developed, pressure ulcers increase hospital stay costs, imposing an enormous burden on our healthcare system [4]. The price of managing a single full-thickness pressure ulcer can be as much as $70 000, and the United States expenditures for treating pressure ulcers have been estimated at $1.6 billion per year [5], [6]. Despite considerable effort to prevent pressure ulcers, prevalence figures remain unacceptably high. In 2009, the National Center of Health Statistics reported that more than 10% of the nursing home residents had developed a pressure ulcer [7]. According to the Agency for Healthcare Research and Quality, among hospitalizations involving pressure ulcers as a primary diagnosis, about 1 in 25 admissions ended in death [8].

The most effective care for an at-risk patient is to relieve the pressure. A common practice in hospitals is repositioning bed-bound patients every 2 h [9]. However, this fixed schedule does not take into account the patient's physiological state and clinical history. Studies have shown that the risk of pressure ulcer development is influenced by several factors including blood pressure, infection, disease conditions, age, sex, and even skin's fragility and malnutrition [10]. Chronic diseases including diabetes, vascular disease, and nervous system disabilities affecting mobility can also indirectly speed up the pressure ulcer formation. Since each patient has a different risk level, some expectedly need more frequent pressure relief than others.

The growing nursing shortage and escalating demands on the nursing staff make it increasingly difficult to provide the same level of service to all of the patients [11]. In 2000, the shortage of nurses was estimated at 6%. This shortage is expected to grow to 20% by 2015 and, if not addressed, to 29% by 2020 [12]. It is important to find ways to better leverage nursing staff and provide the same or better care with fewer nurses.

We previously developed a system that assesses the risk of pressure ulcer development and tracks at-risk body parts using a commercial pressure mapping platform [13], [14]. In this paper, we extend this system by presenting an algorithm for finding a nurse-effort optimal repositioning schedule that prevents pressure ulcer formation for a finite planning horizon.

The paper is structured as follows. In Section II, we put our work into context by discussing related work. In Section III, we propose our finite-duration repositioning schedule that optimizes nurse effort while preventing pressure ulcers. In Section IV, we discuss our constrained shortest path (CSP) solution to find an optimal patient repositioning schedule. Section V presents an empirically driven model for the tissue stress evaluation during loading and recovery periods. Section VI reports experimental results based on actual data from a pressure mat

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platform. In Section VII, we discuss practical applicability of our algorithm in a hospital setting. Finally, in Section VIII, we conclude and discuss future directions for our research.

II. Related Works

Pressure ulcers are dangerous to the patient and can be difficult and costly to treat. Consequently, nursing homes and hospitals usually have prevention programs, such as manual or automated regular pressure shifting and using various cushions with pressure relief components. Higher risk patients are monitored more carefully and repositioned more often than low-risk patients.

Risk level is commonly determined by the Braden pressure ulcer risk assessment chart [15]. Various factors limit effectiveness of this method, especially in the case of Deep Tissue Injury where underlying tissue can be compromised long before the wound is visible [16].

There are other technologies currently available such as passive pressure map/distribution tools [17] and active lifting devices (e.g., beds with moving parts), air mattresses [18], pillows, foam wedges, and soft cushions, which are used to dynamically change the body position of patients [19], [20]. Due to cost and durability, passive pressure relief is more common, using bedding or seat cushions with no active components. Compression and distortion of those materials decrease effectiveness over time [21].

Dynamic cushions redistribute interface pressure through automatic cyclical inflation and deflation of the cushion [22]. Due to the high price of commercial automated air fluidized beds, they are usually used only for the patients with already existing wounds and critical conditions [23]. Other dynamic approaches in a research stage include smart technologies with high density sensors and tiled architectures that have more accurate tilt and recline systems [24].

These solutions all focus on new technologies to redistribute pressure. Another direction is to use existing resources, such as nursing staff, more efficiently. In [25], the authors implemented a nurse rostering system that ensures every rostering decision complies with a mixture of hard hospital rules and soft nurse preferences. In our earlier work, we presented a preliminary study introducing the idea of scheduling patient repositioning based on time–pressure exposure for different regions of skin [13]. In that work, we proposed a greedy heuristic to minimize nursing effort by maximizing the average time interval between posture changes.

Our previous work in this field formalized the concept of nursing effort and applied it to posture scheduling by correlating position changes and nursing effort [26]. It presented a formal optimization that creates a repositioning schedule to prevent ulcer with minimum nursing effort for fixed decision intervals and a finite planning horizon. In that paper, we solved the optimization problem by mapping it to the CSP.

This paper extends the previous work presented in [26] by defining a stress accumulating function that works with continuous pressure and by formulating the properties of the stress function along with the proofs for a medically derived special case. Another contribution of the present paper is proving the hardness of the optimization problem through a reduction from the NP-hard CSP. We will also discuss application scenarios in a hospital setting.

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}

III. Problem Formulation

Prolonged pressure exposure can lead to ulcers. The pressure from body weight collapses the capillaries, depriving local tissue of oxygen and resulting in an accumulation of cellular waste products. Most people shift their weight or change positions periodically allowing the tissue to rapidly recover through a higher than normal blood flow in a process known as reperfusion [27]. Unfortunately, bed-ridden and wheelchair-bound patients may not be able to reposition themselves. Such patients need to be periodically repositioned by caregivers or the local vascular supply could be obstructed for too long, leading to tissue necrosis and pressure ulcers [28].

A. Preliminaries

The first step in creating a repositioning schedule is modeling the problem of stress buildup. The body is divided in into at-risk tissue regions, as shown in Table I. For the sake of simplicity, it is assumed the entire region experiences a uniform pressure in a specific posture. This pressure can change as the patient moves or is repositioned. The patient is expected to be positioned in one of a discrete set of possible postures, $q \in X$, where X is the set of all possible postures.

Definition 1 (Predicted Regional Pressure): $P_i(q_k)$ is the pressure on region i based on the posture pressure model for posture $q_k \in X$ from time t_k to t_{k+1}.

The posture-pressure model assumes constant pressure on a region for a given posture. The model is developed per-patient and can be created from a standard model based on patient measurements, or can be measured using a pressure mat for a patient placed in different postures.

Definition 2 (Actual Regional Pressure): $P_i(t)$ is the actual pressure experienced as a function of time for region i. This can be used to calculate ulcer risk using historical data. It can be measured with a pressure mat.

To prevent ulcer formation, a decision is made periodically to either let the patient remain in the same posture or to reposition the patient. A posture schedule Q_K is a K-length sequence of postures

$$\begin{aligned} Q_K =& (q_1, \ldots, q_k, \ldots, q_K) \\ & q_k \in X \end{aligned} \tag{1}$$

where q_k is patient's posture from time t_k to t_{k+1}. Nursing effort will only be required if the patient is to be moved. The patient will be moved at time t_k if and only if $q_k \neq q_{k-1}$.

B. Tissue Stress

Nursing effort can be trivially minimized by never repositioning the patient. However, this will quickly lead to a pressure ulcer. The notion of waste buildup and energy starvation from pressure is encapsulated in the principle of *regional stress*, $S_{i,k}$. When a region is exposed to pressure greater than a threshold $P_{\min}$, stress builds, otherwise stress subsides.

Definition 3 (Cumulative Regional Stress): The body is divided into tissue regions $i = 1, \ldots, N$. Stress is tracked independently for each region:

$$S_{i,k} = \text{Cumulative stress for region } i \text{ at time } t_k. \tag{2}$$

When regional stress exceeds a certain region- and patient-specific threshold, stress recovery is no longer guaranteed and the patient is considered at risk for a pressure ulcer.

Definition 4 (Stress Threshold): The stress threshold S_i^{th} is the maximum stress that can accumulate for region i before the patient is in danger of developing a pressure ulcer.

At this time, the precise regional thresholds for humans are unknown. Animal studies have identified time thresholds for certain fixed pressures and have formulated a general pressure–time relationship [29]. Researchers have identified risk factors for pressure ulcers, including blood pressure, infection, age, sex, and bony areas of the body [10]. These risk factors could lead to different thresholds for each patient. Ultimately, the regional thresholds should be set by the physician on a per-patient basis until more comprehensive models are developed.

The cumulative regional stress $S_{i,k}$ can be calculated from the regional pressure $P_i(q)$ and an accumulating function.

Definition 5 (Φ: Stress Accumulating Function): Given the stress at time t_a, S_a, and pressure function $P(t)$ applied from t_a to t_b, the cumulative stress is

$$S = \Phi_{t_a}^{t_b} \left(S_a, P(t)\right). \tag{3}$$

The cumulative regional stress for region i at time t_k for posture schedule Q_K is

$$S_{i,k}(Q_K) = \Phi_{t_{k-1}}^{t_k} \left(S_{i,k-1}(Q_K), P_i(q_k)\right) \tag{4}$$

for $k = 1, \ldots, K$ and $i = 1, \ldots, N$.

Accumulating Function Properties: Our model allows for potentially diverse accumulating functions. Even so, certain properties must be met for the function to work within the optimization framework. These properties will be proven for the accumulating function developed in Section III-D.

1) Nonnegativity: Cumulative regional stress can never be less than 0:

$$\Phi_{t_a}^{t_b} \left(S_a, P(t)\right) \geq 0. \tag{5}$$

The nonnegativity property is based on the observation that stress represents a buildup of waste products and a depletion of cellular energy reserves. Once stress is at 0, the energy reserves are fully built up and there is no excess waste. It is not possible to improve on this state.

2) Homomorphism: For a pressure function $P(t)$ valid from time t_a to t_c, with $t_a \leq t_b \leq t_c$, the accumulating function should be homomorphic

$$\Phi_{t_b}^{t_c} \left(\Phi_{t_a}^{t_b} \left(S_a, P(t)\right), P(t)\right) = \Phi_{t_a}^{t_c} \left(S_a, P(t)\right). \tag{6}$$

Homomorphism is required for consistency: if a constant pressure is placed on a specific region for example for 45 min before the cumulative stress is calculated, the results should be the identical to stress calculated at the 15-, 30-, and 45-min marks.

C. Nursing Effort

The nursing effort needed to reposition a patient depends on the time and number of nurses required to move the patient from one posture to another. Effort can be computed knowing only the initial and final postures. In general, any function, or even a static table of transition costs is acceptable, provided all costs are nonnegative. Below is one possible such function that we consider for determining nursing effort:

$$\begin{aligned} \Omega(q_i, q_j) &= N_{ij} \cdot (\tau_0 + \tau_{ij}) \\ & q_i, q_j \in X \end{aligned} \tag{7}$$

where N_{ij} is the number of nurses required to reposition the patient from posture q_i to q_j, τ_0 is the average time required for a nurse to come in to the room, and τ_{ij} is the time spent to reposition the patient.

D. Optimization Problem

To find the most resource efficient turning schedule, we are constructing a constrained optimization problem that minimizes the nursing effort for turning procedure while ensuring that no region ever exceeds its stress threshold. The total nursing effort for a K-length turning sequence Q_K is

$$C(Q_K) = \sum_{k=1}^{K-1} \Omega(q_k, q_{k+1}). \tag{8}$$

Assuming the patient will stay in bed for K periods, the optimal schedule is

$$\begin{aligned} Q_K^{(\text{opt})} &= \arg \min_{Q_K \in \mathbb{Q}_K} C(Q_K) \\ & \text{subject to} \quad S_{i,k}(Q_K) < S_i^{\text{th}} \quad \forall\, i, k \end{aligned} \tag{9}$$

where $\mathbb{Q}_K$ is the set of all K-length turning schedules.

E. Hardness

Our scheduling problem can be proven to be NP-Hard through a reduction from the NP-hard CSP problem. The CSP is the problem of finding the lowest cost paths between a source and destination node in a digraph $G = (V, \vec{E})$, subject to multiple nonnegative linear resource constraints on the edges [30].

We will show in Section IV-A how to map our problem to the nonlinear (NL)-CSP problem. However, the hardness proof of our scheduling problem requires a reduction from CSP to our problem. The CSP problem is defined by its edges, edge costs, and resource constraints. Therefore, in this reduction, the resource constraints correspond to stress values and the edge costs correspond to posture transition costs. Because the stress accumulation function (constraints) is based on the posture schedule (independent of transitions), the edges (with per-edge constraints) in the CSP must be mapped to postures.

Formally speaking, edge e_i maps to posture q_i, and a node represents a posture transition from posture q_i (incoming edge e_i) to posture q_j (outgoing edge e_j). The posture schedule Q_K becomes a sequence of edges, or a path through the original graph. The posture transition cost is taken from the CSP edge costs as follows:

$$\Omega(q_i, q_j) = \begin{cases} \infty, & \text{if dstNode}(e_i) \neq \text{srcNode}(e_j) \\ C(e_j), & \text{otherwise} \end{cases} \quad (10)$$

where $C(e_i)$ is the cost associated with e_i in the CSP graph. The infinite cost is assigned to nonadjacent edges to prevent illegal edge sequences. The linear constraints from the CSP can be directly applied to the posture associated with each edge: $P_i(q_k) = R_i(e_k)$, where $R_i(e_k)$ denotes constraint i associated with edge e_k. In our problem, any stress accumulating function [defined in (3)] that satisfies the nonnegativity and homomorphism properties can be used. In this case, the constraints are linear, so for this mapping, we use $\Phi_{t_a}^{t_b}(S_a, P) = S_a + P$.

Since the above reduction is polynomial, if a polynomial time algorithm existed to solve our problem, then CSP would have also been solvable in polynomial time too. Since the CSP is NP-hard, our problem is also NP-hard.

IV. CSP Solution

An optimal posture-changing schedule can be found using a variant of the resource-CSP problem. We consider a variant with NL resource constraints.

A. Mapping to the NL-CSP

For the posture scheduling problem, at discrete times $t_1, t_2, \ldots, t_K$, a decision is made to reposition the patient to a specific new posture or to leave him/her in the same position. A given posture schedule can be thought of as a particular path through a graph encoding all possible decisions. Each node in the path represents the posture chosen at a particular decision point, and each edge can encode the resource usage and cost.

The graph $G(V, E)$ is built in stages, with each stage representing a particular decision point. A stage added at time t_k adds $\|X\|$ nodes $v_1^k, \ldots, v_{\|X\|}^k$, with each node representing a different choice of posture from posture set X. Directed edges ($e_{i,j}^k = (v_i^{k-1}, v_j^k)$) are added connecting postures from the previous stage to postures in the current stage for all i, j. The edge costs correspond to nursing effort: $C(e_{i,j}^k) = \Omega(q_i, q_j)$.

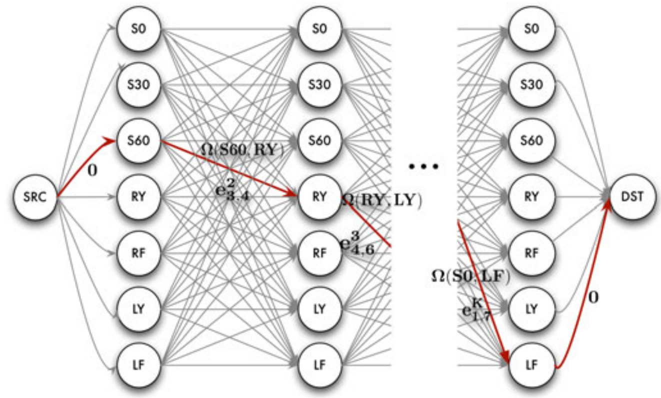

Fig. 1. Example path in the posture scheduling graph. Each path represents a posture schedule.

Each edge is assigned the resource constraints corresponding to the destination posture. The pressure $P_{i,k}$ is used as the parameter for the resource constraints. Since this is the NL-CSP, a nonlinear constraint evaluator can be used, in this case Φ, and the constraints are evaluated using the stress accumulating function. For a given path, the constraints for each region are evaluated as follows:

$$\Phi_{t_{K-1}}^{t_K}(\Phi_{t_{K-2}}^{t_{K-1}}(\ldots, P_{i,K-1}), P_{i,K}) \leq S_i^{\text{th}}. \quad (11)$$

Finally, the source and destination nodes are added. Every posture in the final stage K is connected to the destination node at zero cost, since there is no constraint on the final posture. If the initial posture is unspecified, then the source node is connected to all postures in stage 1 at zero cost; otherwise, it is only connected to the specified initial posture. Fig. 1 shows the constructed scheduling graph G for our set of postures. The highlighted path represents an example of posture turning schedule.

B. k-Shortest Path Approach

A simple approach for solving the NL-CSP is to find the shortest path and see if the resource constraints are violated. If so, the second shortest path is tried. This process is repeated until a path is found that does not violate the constraints [31]. This approach can be easily adapted in our formulation, as it does not depend on linearity of the resource constraints. We use the lazy evaluation of k-shortest path described in [32] to efficiently find the shortest path.

V. Empirically Driven Function

A key to this model is the stress-accumulating function Φ. As discussed earlier, if the pressure a region experiences is greater than $P_{\min}$, stress accumulates, otherwise stress recovers.

A. Stress Accumulating Function

In a previous work, we derived an accumulating function based on constant-pressure injury models and reperfusion recovery models [26]. We will use this function with some modifications to make it work with the continuous accumulating function used here.

In that work, it was assumed that $t_k - t_{k-1} \geq 15$ min. Because full recovery is expected within 15 min, it was considered instant. In this paper, we model recovery as a linear function that can reduce stress from 1 to 0 within 15 min

$$\Phi_{t_a}^{t_b}\left(S_a, P(t)\right) = \begin{cases} \max\left[0, S_a + \int_{t_a}^{t_b} -\frac{1}{15}\, dt\right], & \text{if } P \leq P_{\min} \\ S_a + \int_{t_a}^{t_b} \frac{1}{T_{\text{inj}}(P(t))}\, dt, & \text{if } P_{\min} < P < P_{\max} \\ \infty, & \text{otherwise} \end{cases} \quad (12)$$

where

$$T_{\text{inj}}(P) = T_0 + \frac{1}{\lambda} \ln\left(\frac{P_{\max} - P_{\min}}{P - P_{\min}} - 1\right). \quad (13)$$

Equation (13) is derived from the model presented in [29], where the pressure–time cell injury threshold was formulated for muscle tissue in rats. Equation (12) must be applied to intervals where the pressure is always less than $P_{\min}$, between $P_{\min}$ and $P_{\max}$, or greater than $P_{\max}$. For intervals that include pressure in different regions, the input space can be partitioned and the accumulating function is applied recursively. This equation is defined such that a stress value of 1 is the point at which the patient risks a pressure ulcer. Many factors including weight, patient medical history, and damage to specific areas of skin could assist a doctor to change this threshold for various patients and skin regions.

To the best of our knowledge, there is no study in the literature on modeling ulcer formation from time-varying pressure exposure. Since these data do not exist, we created a time-varying pressure model from a constant-pressure model by assuming linear stress accumulation. However, stress may actually accumulate exponentially, logarithmically, or by some other function. For this reason, the properties of the stress accumulating function are defined in a generic way with the minimum constraints required by our model.

B. Proof of Properties

1) Nonnegativity: In Section III-B1, the nonnegativity property was mentioned. Clearly, the stress-loading model never decreases the stress, and the stress-recovery region is defined such that it can never drop below 0.

2) Homomorphism: Homomorphism (see Section III-B2) is also easily proven. In our stress-recovery and stress-loading models, the pressure determines whether the tissue is being loaded or is in recovery.

For recovery $(P(t) \leq P_{\min})$:

$$\begin{aligned} &\Phi_{t_b}^{t_c}\left(\Phi_{t_a}^{t_b}\left(S_a, P(t)\right), P(t)\right) \\ &= \max\left[0, \max\left[0, S_a + \int_{t_a}^{t_b} -\frac{1}{15}\, dt\right] + \int_{t_b}^{t_c} -\frac{1}{15}\, dt\right] \\ &= \max\left[0, S_a + \int_{t_a}^{t_b} -\frac{1}{15}\, dt + \int_{t_b}^{t_c} -\frac{1}{15}\, dt\right] \\ &= \max\left[0, S_a + \int_{t_a}^{t_c} -\frac{1}{15}\, dt\right] \\ &= \Phi_{t_a}^{t_c}\left(S_a, P(t)\right). \end{aligned} \quad (14)$$

And for loading $(P(t) > P_{\min})$:

$$\begin{aligned} &\Phi_{t_b}^{t_c}\left(\Phi_{t_a}^{t_b}\left(S_a, P(t)\right), P(t)\right) \\ &= S_a + \int_{t_a}^{t_b} \frac{1}{T_{\text{inj}}(P(t))}\, dt + \int_{t_b}^{t_c} \frac{1}{T_{\text{inj}}(P(t))}\, dt \\ &= S_a + \int_{t_a}^{t_c} \frac{1}{T_{\text{inj}}(P(t))}\, dt \\ &= \Phi_{t_a}^{t_c}\left(S_a, P(t)\right). \end{aligned} \quad (15)$$

VI. Experimental Results

We collected pressure data from a commercial pressure mat assembled on a hospital bed for five different subjects. Every subject was positioned in seven different postures, $X = \{$Supine $(S0^\circ, S30^\circ, S60^\circ)$, Right Yearner (RY), Right Foetus (RF), Left Yearner (LY), and Left Foetus (LF)$\}$. The difference between the three Supine postures is the angle of inclination of the bed.

Stress is only tracked for a finite number of at-risk regions. These regions and the postures which induce loading pressures on these regions are tabulated in Table I. The regional pressure model is different for each subject, which can lead to vastly different turning schedules. For instance, Subject #2 has less than $P_{\min}$ pressure on the left buttocks for postures S30° and S60°, and Subjects #4 and #5, the pressure is concentrated on the sacrum, and not on left/right buttocks in the supine posture. This leads to transitions between supine and left/right postures not found with the other subjects.

A. Data Collection Platform

A force-sensing array (FSA) [33] was used to collect pressure data from a hospital bed. The FSA system is a flexible mat that contains 2048 (32×64) uniformly distributed resistive sensors with a sampling frequency of 1.7 Hz. The sensor mat is thin and flexible, and covers the total contact area between the subject and the bed. The FSA system uses the FSA 4.0 software and measures interface pressure between 0 and 100 mmHg.

B. Posture Transition Table

Major repositionings from side postures to the Supine position or from one side to another side often require two nurses, while the minor changes such as going from Foetus to Yearner in the same side or changing the inclination of the torso portion of the bed can be accomplished by only one nurse (changing inclination, in most electric hospital beds, is accomplished by pushing a button). The cost is calculated using (7), with the results shown in Table II.

TABLE II
NURSING EFFORT $\Omega(q_i, q_j)$ REQUIRED TO REPOSITION PATIENTS

	S0°	S30°	S60°	RY	RF	LY	LF
S0°	0						
S30°	τ_0	0					
S60°	τ_0	τ_0	0				
RY	$2(\tau_0+10)$	$2(\tau_0+10)$	$2(\tau_0+10)$	0		*Symmetric*	
RF	$2(\tau_0+10)$	$2(\tau_0+10)$	$2(\tau_0+10)$	τ_0+5	0		
LY	$2(\tau_0+10)$	$2(\tau_0+10)$	$2(\tau_0+10)$	$2(\tau_0+15)$	$2(\tau_0+15)$	0	
LF	$2(\tau_0+10)$	$2(\tau_0+10)$	$2(\tau_0+10)$	$2(\tau_0+15)$	$2(\tau_0+15)$	τ_0+5	0

We assume it takes about 5 min for a nurse to come into the room to move the patient, so $\tau_0 = 5$ min. Also, according to the current empirical data in hospitals, it takes almost 10 min for each nurse to reposition a patient from a side posture to the Supine position, including wearing a gown and sanitizing hands before and afterword. This time increases to almost 15 min for turning the patient from one side to another side. According to Table II, for example, going from right Yearner to Supine takes two nurses 5 min to get there and ten minutes to reposition the patient for a total of $\Omega(RY, S0°) = 30$ min. These are all typical numbers chosen to report our experimentation. In general, our formulation can use any other predefined values.

C. Treatment Scenarios

The treatment scenarios used in this paper is adapted from our previous work [26]. These four scenarios simulate typical patient conditions that may happen in acute care centers.

1) Sc1: All of the body areas are healthy without any symptom of ulceration.
2) Sc2: Reddened skin on the right and left buttocks.
3) Sc3 : Reddened skin on the central sacrum area.
4) Sc4: Reddened skin on the left ankle and left back.

For each at-risk region, we define a risk threshold (S_i^{th}) corresponding to the maximum time interval that an average permissible pressure will cause no harm. Studies have shown that, depending on the body structure and the physiological state, patients can tolerate a turning schedule of 2–5 h before developing an ulcer [34]. Based on this, all healthy regions are assigned a risk threshold corresponding to 3 h of permissible exposure for an average pressure, and reddened regions are assigned a threshold corresponding to an hour and a half of exposure.

Note that in our experimentation, we intentionally chose these simple thresholds to better demonstrate the properties of our turning schedule. In general, our formulation can adopt any S_i^{th} values predefined by a physician.

D. Computational Complexity

The regional pressures for all postures were determined separately for five subjects by asking them to lie in each position on a pressure mat covered hospital bed. The turning schedule optimization problem introduced in Section III was solved with parameters $T = 10.5$ h and $\Delta t = 45$ min. Fig. 3 shows the median of turning schedule's computational time across all five subjects and four scenarios versus planning horizon for different decision intervals. For $\Delta t = 15$ min, the schedule can be obtained relatively quickly for 5 h ahead. By decreasing the resolution of decision making to $\Delta t = 30$ min, the planning horizon can be increased up to 9 h. In our experiments, by considering the nursing visit interval of $\Delta t = 45$ min, we could stretch the planning horizon to $T = 10.5$ h. Beyond 10.5 h, it will be computationally very intensive to solve this optimization problem. However, the planned schedule is based on a pressure-model based on a standard set of postures. The actual pressure loading on different regions will be frequently updated, so it is not necessary to predict too far into the future.

E. Results

Table III shows the sequence of computed postures for all the subjects. The cumulative regional stress for three at-risk regions that may have red spots in different scenarios for Subject #3 is also shown in Fig. 2. This stress was normalized by dividing by the stress threshold for an effective threshold of $S_i^{\text{th}} = 1$.

In the first scenario (Sc1), a trivial solution is to always move from left to right sides every 2–3 h because there is no overlap in body regions. Fig. 2(a) shows that the stress reaching to the threshold in left and right regions is the main reason for repositioning from one side to another side in Sc1. On the other hand, in Table III, for Subject #2, we see transitions from the left side to the Supine. This occurs because this subject is not placing excessive pressure on the left regions in the posture S60°.

The third scenario (Sc3) is similar to Sc1, except the sacrum has a red spot, forcing no subject to choose Supine for more than 1.5 h. Fig. 2(c) shows that stress in left and right buttocks increases to the threshold in left and right sides, respectively, and gets reset in the other side postures.

One or the other buttock is an at-risk region for every posture in scenario two (Sc2), so Sc2 results in a turn every hour and a half, alternating between postures loading the left buttock and those loading the right buttock. The exceptions are Subjects #4 and #5 that put less than $P_{\min}$ pressure on right and left buttocks for the posture S0°. Fig. 2(b) shows stress increasing alternating between left and right postures with shorter duration than Fig. 2(c) since there are red spots in both buttock areas.

In scenario four (Sc4), since both red spots happen to be in the left side, no subject can stay in the left side postures longer than 1.5 h. Fig. 2(d) shows since the left buttock is exposed to pressure more than $P_{\min}$ for both S0° and left Yearner, stress keeps increasing in left buttock in the first 3 h of schedule even though a repositioning happens after 1.5 h.

However, for Subject #2 in Sc4, we can still see transitions happen between left side and Supine posture. This shows being in right side has higher overall cost even though the duration in the left side is noticeably short causing more frequent turning. The more frequent repositioning results in more nursing cost. The last column in Table III shows $C(Q_T)$, the total nursing effort for $T = 10.5$ h schedule that was defined in (8).

TABLE III
TURNING SCHEDULES FOR EACH SUBJECT AND SCENARIO

Trial	Time Duration (0:45, 1:30, 2:15, 3:00, 3:45, 4:30, 5:15, 6:00, 6:45, 7:30, 8:15, 9:00, 9:45)	N_{opt}	$C(Q)$
Subject #1			
Sc1	RF → LF → RF → LY	320	120
Sc2	RF → LY → RY → LF → RY → LF → RF	256	240
Sc3	RF → LY → RF → LY	320	120
Sc4	S0° → LY → RY → LF → RY	192	150
Subject #2			
Sc1	LF → S0° → LY → S30°	720	90
Sc2	LY → S60° → LF → S60° → LF → S60° → LY	1080	180
Sc3	RY → LF → S0° → LY	48	100
Sc4	S30° → LY → S30° → LY → S30°	1476	120
Subject #3			
Sc1	RY → LF → RY → LF	320	120
Sc2	RY → LY → RF → LY → RY → LY → RY	256	240
Sc3	LY → RF → LF → RF	320	120
Sc4	S0° → LY → RY → LF → RY	64	150
Subject #4			
Sc1	S0° → LF → S0° → RF	320	90
Sc2	S0° → LF → S0° → RY → S0°	272	120
Sc3	LY → S0° → LY → RY	64	100
Sc4	RY → S0° → RF → S0°	96	90
Subject #5			
Sc1	LY → S0° → LF → S0°	320	90
Sc2	S0° → RY → S0° → LY → S0°	272	120
Sc3	LF → RF → S0° → RY	64	100
Sc4	LF → S0° → RY → S0°	96	90

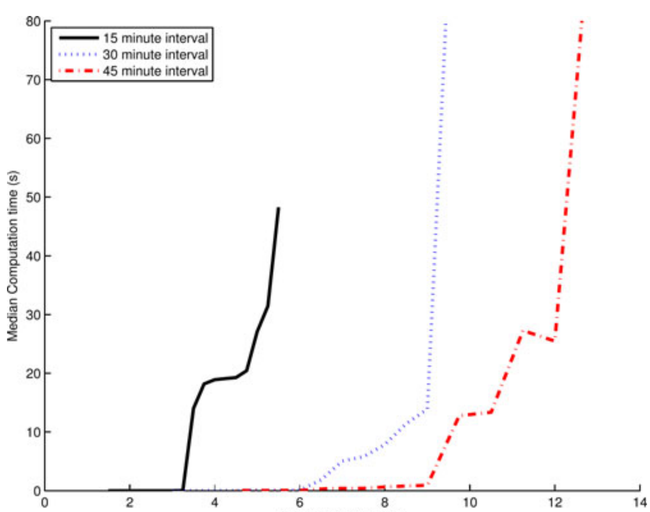

Fig. 2. Cumulative regional stress for three at-risk regions in Subject #3.

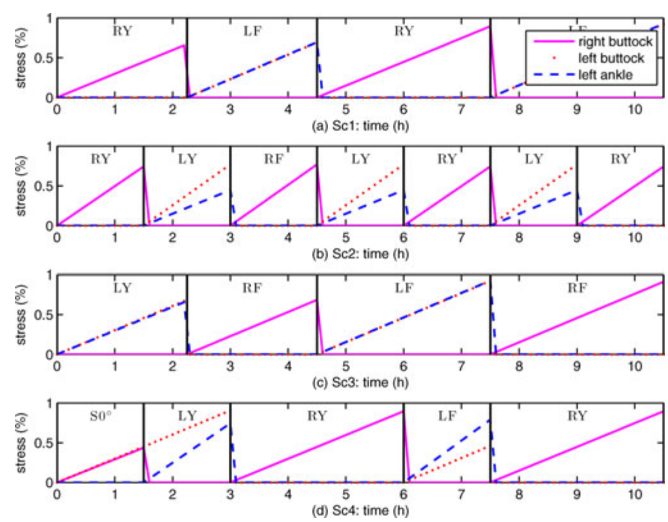

Fig. 3. Median computational time across all subjects and scenarios versus planning horizon for different decision intervals. (a) Sc1: time (h). (b) Sc2: time (h). (c) Sc3: time (h). (d) Sc4: time (h).

In general, the schedules provided in the Table III are not unique. The next to the last column in Table III shows the number of optimal solutions ($N_{\rm opt}$) that satisfy the constraints out of $\|X\|^K$ possible paths, where $\|X\| = 7$ is the number of postures in posture set and $K = 14$ is the length of posture schedule. The number of solutions can vary from 48 for Subject #2, Sc3, to 1476 for Subject #2, Sc4. The schedule can be chosen arbitrarily, or by looking at some other factor, such as patient comfort (Supine is frequently preferred to other postures).

VII. Discussion on Practical Aspects

Acute centers (e.g., hospitals and wound clinics) could use this work to greatly reduce required nursing resources by more efficiently allocating them to the patients needing the most care. We envision a system in every room that tracks patient stress and sends an alert to the nurses station (just as heart monitors do now) if a patient needs repositioning.

A more advanced system could use a pressure mat to calculate current stress based on actual data and to update the posture-pressure model to attain better prediction accuracy. Our research group has also developed algorithms to recognize posture from pressure mat data [14] and to calculate Braden risk factors from Nurse input and track activity, mobility, and tissue stress [35].

When it is time to move the patient, the system will suggest several possible optimal postures, and make available some suboptimal postures. While the nurses would be encouraged to select from the list of optimal postures, sometimes concerns, such as patient comfort will take precedence. When the nurse repositions the patient, they could enter the new posture so the system can extrapolate stress.

Stress thresholds could be changed for all patients at once to reflect reduced nursing staff, or could be changed on a per-patient/per-limb basis in recognition of risk factors and observations of preulcer conditions, such as skin redness. The per-limb risk factors could easily be set with a touch screen interface featuring a human form.

VIII. Conclusion and Future Work

In this paper, we formulated an optimization problem for finding a nursing effort-optimal posture schedule that avoids pressure ulcers. This problem was shown to be NP-Hard. To the best of our knowledge, this is the first study trying to create a unified model for pressure ulcer formation and prevention based on exposure to and relief from pressure. We developed our tissue stress model using animal studies by various research groups. Using a decision interval of $\Delta t = 45$ min, schedules with a planning horizon up to $T = 10.5$ h could be generated for several healthy subjects. The regional posture-pressure table for each subject was built with data collected using a commercial pressure mat on a hospital bed. When all regional stress thresholds were identical, the results confirmed the standard practice of repositioning patients on a simple fixed schedule. However, if some thresholds were lowered, such as in response to the appearance of red spots (indication of ulcer onset) on some body parts, the generated schedules were much more interesting and hard to guess. This shows the need for such a system to give each patient care customized to his/her needs, while minimizing the nursing effort.

While pressure ulcers have been extensively studied, much remains unknown. For instance, while the length of exposure to constant pressure causing pressure ulcers is known, the effect of varying pressures is unknown. Furthermore, there is no model showing how much rest between pressures is required to fully or partially recover from the initial exposure. Finally, the specific effects of various compounding factors (e.g., fever, anemia, body mass, shear, and temperature) is largely unknown. These are potential research questions for both animal and human studies. Animal studies can be used to get the basic structure of the models, while human studies can fill in the parameter values. Another interesting direction is developing schedules taking into account patient's comfort such as preference to be in Supine posture during visiting hours.

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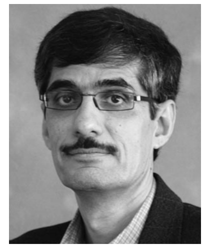

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