A Posture Scheduling Algorithm Using Constrained Shortest Path to Prevent Pressure Ulcers

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Abstract—Pressure ulcer is a severe threat for immobilized and peripheral neuropathic patients such as bed-ridden, elderly, and diabetics. Once developed, the complication of pressure ulcer causes pain, suffering, and longer hospitalization for the patients. Additionally, pressure ulcer management imposes a serious burden on the health care providers. The optimal strategy to deal with pressure ulcers is prevention. The current standard for prevention is to reposition at-risk patients every two hours. But, each patient has different needs based on overall vulnerability and damaged skin areas. A fixed schedule may either result in some patients getting ulcers, or nurses being overworked by turning some patients too frequently. In this paper, we present an efficient algorithm to find a repositioning schedule for bed-bound patients based on their risk of ulcer development. 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. Our patient-specific turning schedule minimizes the overall cost of nursing staff involvement in repositioning the patients while simultaneously decreases the chance of pressure ulcer formation.

Index Terms—Constrained Shortest Path, Posture Scheduling, Pressure Ulcer, Tissue Stress Evaluation.

I. INTRODUCTION

Pressure ulcers (also called bedsores) are injuries to skin and underlying tissues as a result of prolonged pressure. Pressure ulcers most often develop on the skin that covers bony areas of the body, such as the heel, ankles, hips or buttocks. People most at risk are those with medical conditions that limit their abilities to change positions, requiring them to use wheelchairs or confining them to beds for an extended time period [1].

Pressure ulcers can develop quickly and are often very difficult to treat. They are painful and can lead to life-threatening complications. Once developed, pressure ulcers increase hospital stay costs, imposing an enormous burden on our health care system.

The most important care for an at-risk patient is to relieve the pressure. A common practice in hospitals is repositioning bed-bound patients every two hours [2]. However, this fixed schedule doesn’t take into account the patient’s physiological state and clinical history. Studies have shown the risk of pressure ulcer development is influenced by several factors such as blood pressure, infection, disease conditions, age, sex and even fragile skin and malnutrition [3]. Chronic diseases including diabetes, vascular disease, and nervous system dis-abilities affecting mobility, can also speed up the pressure ulcer formation. Since each patient has a different risk level, some expectedly need more frequent pressure relief than others.

Efficient prevention planning based on need in the context of pressure ulcer alleviates the growing nursing shortage [4], and decreases the pressure ulcer formation incidents in the hospitals, thus reducing the resulting treatment costs.

Our main contribution in this paper is to develop a system using a commercial pressure mapping platform that assesses the risk of pressure ulcer development and tracks at-risk body parts. In this work, we have proposed an optimized turning schedule based on a constrained shortest path model that allows care givers to schedule and reposition patient more effectively. The solution to this optimization problem determines minimum number of repositioning to reduce nursing effort required to prevent pressure ulcer formation. It also recommends a sequence of positions (postures) and the time of repositionings for each individual patient.

II. RELATED WORKS

Since treatment of the established pressure ulcers is extremely difficult and costly, the ideal solution is prevention. Nursing homes and hospitals usually set programs to avoid the development of bedsores in bedridden patients, such as pressure shifting on a regular basis and using a cushion with pressure relief components. Higher risk patients are cared more carefully and repositioned more often rather than using a fixed schedule. Risk level is commonly determined by the Braden pressure ulcer risk assessment chart [5]. A nurse fills this chart by entering a number between 1 to 4 for various risk categories based on a visual inspection of the patient. The sum of these numbers roughly represents the inverse level of risk, i.e. usually under 16 indicates at-risk and under 12 shows high-risk patients. However, various factors limit accuracy and effectiveness of this method, especially in the case of Deep Tissue Injury (DTI) that underlying tissue can be compromised by the time the skin actually opens [6].

To facilitate advanced intermittent pressure relief, there are techniques currently available such as passive pressure map/distribution tools and active lifting devices (e.g., beds with moving parts), air mattresses, pillows, foam wedges, and soft cushions, which are used to dynamically change the body position of patients.
Static bedding or seat cushions of various materials are the most common options; however, because these cushions are static designs, pressure redistribution is only momentarily accomplished because progressive loss of this effect occurs from compression and distortion of those materials [7]. Dynamic cushions redistribute interface pressure through automatic cyclical inflation and deflation of the cushion. However, there is a lack of solid scientific research validating their efficacy [8]. Additional approaches to relieve pressure are smart technologies with high density sensors and tiled architectures that have more accurate tilt and recline systems, but they are still in level of laboratory experiments and far from commercialization [9].

Another approach is better utilization of existing treatment resources. Authors in [10] implemented a nurse rostering system that ensures every rostering decision complies with a mixture of hard hospital rules and soft nurse preferences.

In our previous work, we proposed a scheduling technique that more efficiently allocate the existing hospital resources (i.e nurses) for repositioning the patients [11]. In that work, we formulated an optimization problem to determine the maximum average interval between posture changes required to prevent pressure ulcer formation. We then solved it with a greedy heuristic, with the goal of minimizing nursing effort.

Here, we formalize the concept of nursing effort and imply it for position scheduling by considering that certain repositionings require more work from nurses than others. We further provide a mechanism to specify maximum pressure exposure on a per-body part basis. Finally, this problem is optimally solved using a mathematical approach based on the constrained shortest path model for a finite time duration.

III. PRESSURE ULCER PREVENTION WITH OPTIMAL NURSE EFFORT

Bedridden and wheelchair bound patients are particularly vulnerable to pressure ulcers. For such patients, the vascular supply through the capillary network in some body parts could be obstructed for too long by compressive stress due to body weight. The pressure collapses the capillaries and leads to local tissue ischemia and an accumulation of cellular waste products. Eventually, this results in tissue necrosis [12] and pressure ulcers. If pressure is relieved in time, the area rapidly recovers through a higher than normal blood flow in a process known as reperfusion [13].

Every posture exposes the body to a different set of pressures. The high risk regions for developing pressure ulcer are often 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. Fig. 1 shows some of these at-risk regions considered in our study.

We model the non-permanent effects of excess pressure as stress. Stress will build whenever the pressure is above a certain threshold, and recover when the pressure is below this threshold. When stress in any region exceeds a certain region- and patient-specific threshold, the patient is considered to be at risk for a pressure ulcer.

Nurses relieve the stress in high pressure regions by periodically repositioning the patient to shift the pressure. The amount of effort required to do this is based on the number of nurses and the time it takes to move the patient from one position to another.

We present a model of this problem and provide a framework for solving it optimally over a finite duration. Stress is tracked independently for each at-risk region of skin based on the pressure on each region over time. A region-pressure model is developed that gives the nominal pressure in each region for every possible position a patient can lie (see Section IV). An optimal repositioning schedule is computed to minimize nursing effort while ensuring that no region ever exceeds its stress threshold (see Section V).

A. Repositioning Schedule

The goal is to create a finite-duration repositioning schedule that optimizes nurse effort while preventing pressure ulcers. A repositioning schedule $Q_T$ is a $T$-length sequence of postures:

$$Q_T = \{q_1, \ldots, q_k, \ldots, q_T\}$$

where $q_k \in X$ and $X$ is the set of all possible postures (see Fig. 2 for a typical set).

A patient stays in posture $q_k$ from time $t_k$ to time $t_{k+1}$. We assume, the posture interval is fixed; i.e.

$$\Delta t = t_k - t_{k-1} = t_{k+1} - t_k, \quad \forall k \in [1, T]$$

A repositioning occurs at time $t_k$ if and only if $q_k \neq q_{k-1}$. This implies that any posture the patient goes to will be held for an integer multiple of $\Delta t$.

B. Tissue Stress

Tissue stress is based on the effects of prolonged oxygen deprivation and waste buildup. This happens when the capillary network in a region collapses, which happens when pressure is over a certain threshold $P_{min}$. When pressure is less than $P_{min}$, tissue starts to recover. More details of this model can be found in [11].

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

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

Currently there are only partial models for tissue stress, and none has been proven to have a specific predictive power.
for ulcer formation. Further, while some patient’s risk factors (blood pressure, infection, disease conditions, age, and sex) and region risk factors (bony protuberances, uncalled tissue) are known, there is no mathematical model relating these to stress accumulation. Therefore, it is essential to provide caregivers with a tool to customize the model parameters on a patient and region specific level. In our model, that tool is the stress threshold.

**Definition 2. (Stress Threshold)** The stress threshold, \( \sigma_i^{th} \) is the maximum stress that can accumulate for region \( i \) before the patient is in danger of developing a pressure ulcer.

**Definition 3. (Region Pressure)** \( P_i(q_k) \) is the maximum average pressure on region \( i \) from \( t_k \) to \( t_{k+1} \). This is based on the posture pressure model for \( q_k \in X \) as defined in Eqn. (9).

**Definition 4. (Φ: Stress Accumulating Function)** Given the previous stress, \( S_{i,k-1}(Q_T) \), and a constant pressure \( P_i(q_k) \) applied for \( \Delta t \) time interval for schedule \( Q_T \), the cumulative stress is:

\[
S_{i,k}(Q_T) = \Phi(S_{i,k-1}(Q_T), P_i(q_k), \Delta t)
\]

for \( k = 1, \ldots, T \) and \( i = 1, \ldots, N \).

**C. Nursing Effort**

The nursing effort required to reposition the patient depends on the time and number of nurses required to move the patient from one posture to another. In a simplified sense, this effort can be estimated knowing only the initial and final postures.

We define a formula for nursing effort:

\[
\Omega(x_i, x_j) = N_{ij} \cdot (\tau_0 + \tau_{ij})
\]

where \( N_{ij} \) is the number of nurses required to reposition the patient from posture \( x_i \) to \( x_j \), \( \tau_0 \) is the average time required for a nurse to come in to the room, and \( \tau_{ij} \) is the time it takes to reposition the patient.

Eqn. (5) is only one way to measure nursing effort. Any other definition of the effort function is permitted in our optimization problem (see Section III-D), provided all entries are non-negative.

**D. Optimization Problem**

The total nursing effort for a \( T \)-length sequence \( Q_T \) is:

\[
C(Q_T) = \sum_{k=1}^{T-1} \Omega(q_k, q_{k+1})
\]

Assuming the patient will stay for \( T \) periods, then the optimal schedule is:

\[
Q_T^{(opt)} = \arg \min_{Q_T \in Q_T} C(Q_T)
\]

subject to \( S_{i,k}(Q_T) < S_i^{th} \) \( \forall i, k \)

where \( Q_T \) is the set of all \( T \)-length schedules.

**IV. Tissue Stress Model**

Creating an optimal posture repositioning schedule requires the ability to predict the accumulated stress based on the choice of posture at each decision point. The tissue stress model utilizes a region pressure model and a stress accumulation function which together provide this predictive ability. The region pressure model estimates the pressure for each region and posture based on past measurements, and the tissue accumulation function is based on animal studies of deep tissue injury.

**A. Region Pressure**

The region pressure, \( P_i(x) \), is the pressure exerted on region \( i \) for posture \( x \) in \( X \) for the time interval \( \Delta t \). A worst case estimate, the maximum average pressure, is used to compute this value:

\[
P_i(x) = \max_{s \in S_i(x)} \left\{ \frac{1}{\Delta t} \int_0^{\Delta t} p_s(t) \, dt \right\}
\]

where \( S_i(x) \) is the set of all sensors covering region \( i \) for posture \( x \). The worst-case estimate is used since overestimating stress is safer for the patient than under estimating stress.

**B. Defining a Stress Accumulating Function**

For a given pressure, stress can either increase through stress loading, or decrease through stress recovery. These models are developed separately, then combined.

1) Stress-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 [14]. 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 [15] refined this concept and formulated the pressure-time cell injury threshold for muscle tissue:

\[
P(T) = \frac{P_{max} - P_{min}}{1 + e^{\lambda(T - T_0)}} + P_{min}
\]

where the constants of pressure-time injury threshold were chosen in to be \( P_{max} = 232 \text{mmHg}, P_{min} = 37 \text{mmHg}, \lambda = 0.15 \text{min}^{-1} \), and \( T_0 = 95 \text{min} \). According to this model, for each body part, any pressure-time point above this threshold results in ulcer formation.

In order to find the critical time of exposure, \( T_{inj} \), for a specific amount of pressure, \( P \), we rewrite Eqn. (10) in terms of time as the function of pressure.

\[
T_{inj}(P) = \begin{cases} \infty & P \leq P_{min} \\ 0 & P > P_{max} \\ T_0 + \frac{1}{\lambda} \ln \left( \frac{P_{max} - P_{min}}{P - P_{min}} - 1 \right) & \text{otherwise} \end{cases}
\]

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Therefore, the tissue stress accumulating function for stress-loading pressures, \( \Phi_L(\cdot) \), is

\[
\Phi_L(S_0, P, \Delta t) = S_0 + \frac{\Delta t}{T_{\text{inj}}(P)}
\]  

(12)

2) Stress-Recovery Model: When a region is exposed to a safe pressure, \( P_i(q_k) \leq P_{\text{min}} \), the stressed tissue enters a phase of recovery. The investigation on the off-loaded recovery interval shows that recovery time increases with load duration and load pressure [16].

Authors in [17] have shown a recovery time of about 15 minutes after 40 minutes of continuous heel pressure loading by measuring heel blood perfusion by means of laser Doppler imaging. They also compared the recovery response of full relief and partial relief. The experimental results of these studies indicate the recovery time is in the order of 15 minutes, which is effectively instantaneous compared to standard repositioning intervals greater than 1 hour.

Unfortunately, there is very little, if any, clinical human data in the pressure ulcer formation and also to the best of our knowledge there is no recovery model. We use the instantaneous recovery in this study, meaning the tissue stress accumulating function for the recovery model is:

\[
\Phi_R(S_0, P, \Delta t) = 0
\]  

(13)

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

C. Combined Stress Model

Combining the two tissue stress models, (12) and (13), results in tissue stress accumulating function:

\[
\Phi(S_0, P, \Delta t) = \begin{cases} 
0 & \text{if } P \leq P_{\text{min}} \\
S_0 + \frac{\Delta t}{T_{\text{inj}}(P)} & \text{otherwise}
\end{cases}
\]  

(14)

V. A CONstrained SHortest PATH SOLUTION

An optimal posture-changing schedule can be found using a variant of the resource-Constrained Shortest Path (CSP) problem [18] that allows non-linear constraints.

A. Mapping to the CSP

For the posture scheduling problem, every \( \Delta t \) minutes 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 \( v^k_i, \ldots, v^k_{|X|} \), with each node representing a different choice of posture from posture set \( X \). In a posture schedule, exactly one posture is chosen at each time. This is facilitated by adding a directed edge \( e^k_{i,j} = (v^k_i, v^k_j) \). The cost associated with the edge \( e^k_{i,j} \) is the transition cost between

\[
\text{postures } x_i \text{ and } x_j, \quad \Omega(x_i, x_j).
\]

The resource constraints are \( \langle S_{1,k}, \ldots, S_{N,k} \rangle \), where each element is the cumulative stress at time \( t_k \) for each at-risk region.

Finally, the source and destination nodes are added. Every posture in the final stage, \( T \), is connected to the destination node at \( 0 \) 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.

B. k-Shortest Path Approach

Our approach for solving the 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 [19]. This approach can be easily adapted to our problem, as it does not depend on linear resource constraints.

The \( n \)th optimal schedule can be found with a \( k \)-shortest path algorithm. We use the lazy evaluation of \( k \)-shortest path, described in [20], to efficiently find the shortest paths.

VI. EXPERIMENTAL RESULTS

To verify the effectiveness of the proposed CSP optimization algorithm, we collected pressure data from a commercial

<table>
<thead>
<tr>
<th>Table I</th>
<th>Nursing Effort ( \Omega(x_i, x_j) ) Required to Reposition Patients</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>S0°</td>
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<tr>
<td>S0°</td>
<td>0</td>
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<td>S30°</td>
<td>( \tau_0 )</td>
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<td>S60°</td>
<td>( \tau_0 )</td>
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<td>RY</td>
<td>2(( \tau_0+10 ))</td>
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<td>RF</td>
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<td>LF</td>
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pressure mat for three different subjects lying on a hospital bed. Every subject was positioned in seven different postures, $X = \{\text{Supine (S0°, S30°, S60°)}, \text{Right Yearner (RY)}, \text{Right Foetus (RF)}, \text{Left Yearner (LY)}, \text{and Left Foetus (LF)}\}$. Pressure map images for the postures are shown in Fig. 2, with lighter colors representing higher pressure, except for white which is no pressure. The difference between the three supine postures is the angle of inclination of the bed.

A. Data Collection Platform

A Force-Sensing Array (FSA) [21] was used to collect pressure data from a hospital bed. The FSA system is a flexible mat that contains 2048 (32 x 64) uniformly distributed resistive sensors with a sampling frequency of 1.7 Hz. The sensor mat covers the total contact area between the subject and the bed and is light, thin and flexible. The FSA system uses the FSA 4.0 software and measures interface pressure between 0 to 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 is accomplished by pushing a button, but many immobilized patients are incapable of this). The cost is calculated using Eqn. (6), with the results shown in Table I. We consider it takes about five minutes for a nurse to come into the room to move the patient, so $\tau_0 = 5$ min. From the table, going from right yearner to supine takes two nurses five minutes to get there and ten minutes to reposition the patient for a total of $\Omega (\text{RY}, \text{S0°}) = 30$ min.

C. Treatment Scenarios

We created four treatment scenarios based on typical patient conditions. The first is for immobile, but otherwise healthy patients, and the other three are based on patients with reddened areas of skin. Reddened skin is the first symptom of ulcer formation. By reducing pressure exposure to these areas, pressure ulcers can often be prevented. The list of scenarios follows.

Sc1 All of the body areas are healthy without any symptom of ulceration
Sc2 Reddened skin on the right and left buttocks
Sc3 Reddened skin on the central sacrum area
Sc4 Reddened skin on the right ankle and left back

Studies have shown that, depending on the body structure and the physiological state, patients can tolerate a turning schedule of two to five hours before developing an ulcer. Based on this, all healthy regions are assigned a risk threshold $S_i^{(t)}$ corresponding to three hours of permissible exposure for an average pressure, and reddened regions are assigned a threshold corresponding to an hour and a half of exposure.

In general, physicians may choose to raise or lower $S_i^{(t)}$ for every region based on overall patient’s risk, or lower specific higher risk regions. In this experiment, our scenarios are kept intentionally simple to better demonstrate the properties of the optimal schedule.

D. Results

The regional pressures for all postures in Fig. 2 were determined separately for three subjects by asking them to lie in each position on a pressure mat. The CSP optimization problem introduced in Section III was solved with parameters $T = 9$ hrs and $\Delta t = 45$ min.

Table II shows the sequence of computed postures for all of the subjects. In the first scenario (Sc1), an obvious solution is to always move from left to right sides every three hours because there is no overlap in body regions. For the first subject, we see transitions from the left side to the supine. This occurs because for this subject, the patient is not placing excessive pressure on the left buttock in the supine position. The third scenario (Sc3) is similar, except the sacrum has a red-spot, forcing no subject to choose supine.

One or the other buttock is an at-risk region for every posture, so scenario two (Sc2) results in a turn every hour and
a half, alternating between postures loading the left buttock and those loading the right buttock. In scenario four (Sc4), it was possible for the first subject to completely avoid postures with the left back and right ankle, resulting in a very low-cost schedule. The other subjects had to be repositioned every one hour and half. The more frequent repositioning results in more nursing cost. The last column in Table II shows \( C(Q) \), the total nursing effort for \( T = 9 \) hrs schedule that was defined in Eqn. (6).

VII. CONCLUSION AND FUTURE WORK

In this paper, we presented a scheduling algorithm based on the constrained shortest path optimization problem: (a) to prevent ulcer formation, and (b) to minimize nursing effort. The regional pressure model for each posture was built using data from healthy subjects taken with a commercial pressure mat on a hospital bed. Due to the lack of human study in the ulceration modeling, we used a pressure-time cell injury model for rats. As far as recovery model, we assumed an instantaneous recovery based on data from blood perfusion measurement in the human heel [17]. This cell recovery model may not be accurate since the investigation on fatigue duration in athletes muscles shows after severe muscular contraction recovery of fatigue is largely complete in a few minutes, but is not entirely completed for many hours. In a follow-up study, we intend to design some animal studies for extracting recovery model both after fully off-loading and under partial loading to address the lack of experimental results in human cell recovery modeling. Furthermore, patients strongly prefer the supine position to any other position, so the model needs to be modified to consider patient preference.

REFERENCES