An Automated On-Bed Rehabilitation System Design Based on Pressure Sensory Data Analysis

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***Abstract*—On-bed physical exercise is significant and necessary during rehabilitation process for patients with motor disorders. An automated, self-managed on-bed rehabilitation system is in demand. Such a system can be achieved and monitored with pressure mapping and posture classification. In this paper we present an automated physical rehabilitation system developed based on pressure mapping and advanced sensory data mining for bed ridden patients to conduct self-rehabilitation. The system is developed with three modules: 1) sensing module; 2) posture recognition module and 3) evaluation & feedback module. Sensing module provides raw data and generates pressure map; Posture recognition module processes pressure data and recognizes postures; Evaluation & feedback module is designed to provide condition evaluations and rehabilitation recommendations. Such a design can automatically provide instructions and guidance for next step exercise, without the involvement of physical therapist. The experimental results have demonstrated the effectiveness of this system. It could serve as a prototype of automated self- rehabilitation system.**

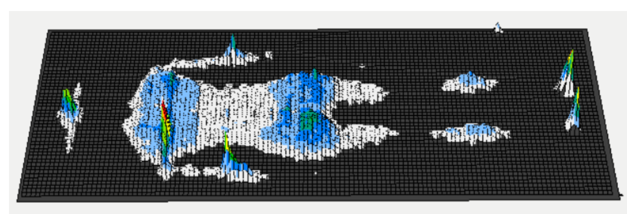
***Keywords*—automated rehabilitation, on-bed rehabilitation, pressure sensing, data analysis**

I. Introduction

Physical rehabilitation is well recognized to provide accelerated and long lasting benefits to patients [1]. The patients who cannot move or walk normally after illness, injury or surgery need on-bed motion exercises to maintain physical strength and mobility. The on-bed motion exercises can help stimulate motor nerves to maintain or improve muscles and joints functionality. Traditional physical rehabilitation exercises are monitored and evaluated manually by physical therapist, which involves a large cost in tracking the rehabilitation progress. Therefore, there is a need to develop automated physical rehabilitation exercise systems.

A key goal of many systems for physical rehabilitation is automation. Many systems exist in other domains that attempt to automate physical rehabilitation, enabling simpler or even self-rehabilitation. Candelieri *et al.* demonstrated a self-rehabilitation system for elders to manage their own rehabilitation using wearable sensors [2]. Work by Lin *et al.* proposes work for automated analysis of rehabilitation exercises [3]. Similar to our own system, Yousefi *et al.* made a smart bed system except that it was in the domain of automated Ulcer prevention [4]. All existing well developed automated rehabilitation systems are based on robots, wearable sensors, and assistive tools, but almost none of them is designed for bed rehabilitation.

(a)



(b)

Fig. 1. System setup. (a) pressure sensor array mat deployment; (b) pressure measurement.

Robotics and related devices are too expensive to be applied to bed rehabilitation systems. An alternative solution is using low-cost sensors, especially pressure sensors, which have been investigated and applied to build on-bed rehabilitation systems. Pressure sensor based bed rehabilitation systems are implemented through posture recognition using various methodologies. [5] used low resolution pressure maps with SVM to recognize postures. The work of [6] used image binarization to classify eight postures. Finally the work in [7] used autoencoder neural networks to classify the postures. All of these regardless of purpose used pressure maps, and this will be the basis of our system to collect data as well [8],

[9]. Although these works achieved good performance on posture recognition, they failed to provide further evaluations and feedback to enable self-rehabilitation.

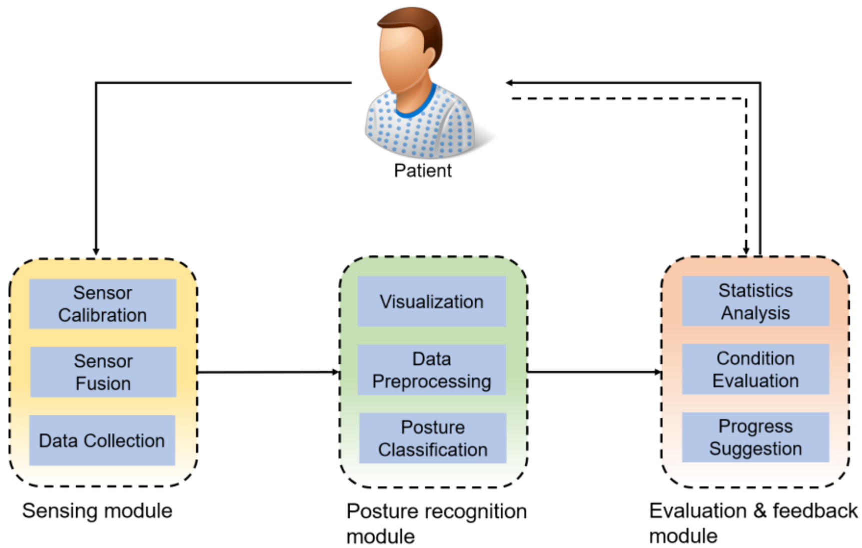


Fig. 2. System architecture of proposed automated pressure sensing based bed rehabilitation system.

Other than the existing work on bed rehabilitation systems, we present a complete automated bed rehabilitation system. This system is not only able to perform posture recognition, more importantly, it is able to conduct information analysis, condition evaluation and provide rehabilitation suggestion based on user profile, rehabilitation guidelines and posture recognition results. Such a system provides a completely automated solution for on-bed rehabilitation, enabling users to perform self-rehabilitation without a physical therapist. To be noted, this work focuses on the system design and module development. The details of posture recognition can be reached in our previous work [10].

II. System Design and Development

In this work, we design the automated bed rehabilitation system with three modules. As shown in Fig. 2, this system is composed of sensing module, posture recognition module and evaluation & feedback module.

A. Pressure Sensing Module

1) Pressure Sensor Mat: The pressure sensor mat shown in Fig. 1(a) is produced based on piezo resistors. These resistors are deployed between two layers of nylon fabric. With applied pressure, the resistance changes can indicate pressure levels. As the nylon fabric is flat, soft and comfortable, it is particularly suitable for human body pressure measurement. Fig. 1(b) shows the pressure measurement of human body with a supine rest posture.

The pressure sensor array used in this work is 48 sensors wide by 128 sensors long for a total of 6144 square sensors within the dimensions 33 × 73 inches region. The pressure values of each of the sensors are calibrated to a range of 0-150mm Hg or pressure which are mapped by sending a voltage signal to the computer.

2) Pressure Sensor Calibration: Before using the sensing mat, we have to calibrate the mat due to inaccurate readings. These readings come from significant values of 10-20mm Hg pressure despite nothing is being on top of the mat. To address this problem we need to calibrate the mat to be in the range of 0-150mm Hg and to ensure the sensitivities of various sensors are the same.

The calibration process involved placing the mat in between two wooden plates and one air bag used to control the pressure. These plates were inserted into a series of wooden slots that would hold the mat in place during calibration. The airbag is connected to a pressure pump that holds a measure of the pressure. Then the pressure changes can be made by the pressure pump. Once this was done, the calibration file was uploaded to the mat and the calibration was finished.

B. Posture Recognition Module

1) Data Processing: As shown in Fig. 3, the framework of posture recognition module, data that comes through the mat must first be pre-processed. This involves passing data through a Gaussian filter for de-noising especially with noisy signals that occur because of voltage leakage. There is also a median filter to purposely blur the images. Such data pre-processing operation facilitates posture recognition. Images are also binarized to further focus on the image structure rather than any individual pressure image values.

When it comes to data visualization, the raw data is structured as 48 by 128 sized image for all the individual pressure sensors. The image is then displayed as a gray-scale image using an arbitrary color map.

2) Posture Classification: The data processing is followed by the operation and classification stages. As show in Fig. 3, operations include normalization, binarization and segamentation. These operations are employed to further generalize and optimize the data. In this work, seven postures were tested supine rest, head lifts, leg lifts, supine flexed, heel slides, sit-ups, and transition. During the testing of the postures all the individual frames were passed through the recognition engine including postures that weren't ideal exercise postures. These transition postures were classified collectively as a "transition" posture.

Besides the traditional classifiers such as SVM, kNN and CNN, in this work we also tested a region-based classifierproposed by us. Basically, the pressure map of patient body can be regarded as the combination of different parts/regions including head, limbs, and torso. Since the signals are pressure signals of patient body, they are relatively static with only slight change of a certain part/region. The similarity of two regions of two postures can be calculated based on the Euclidean distance of their centroids. The distance can be represented by

$$d_{ij} = 3.5 * \| C_i, X_j \|_{Eucl.} + | C_i(m) - X_j(n) | \quad (1)$$

where Ci is the ith centroid, Xj is the jth neighbor, and $Ci(m)$, $Xj(n)$ represent their pressure values, respectively.

When calculate the similarity, the distance scores are not evenly counted, instead, a signature is defined to represent the most dominant region of a certain posture, thus the overall similarity can be represented by

$$S = k_i \cdot s_i + (1 - k_i) \sum_{j=1}^{5} s_j \quad (2)$$

where S is the final similarity, k_i is the weight of signature limb, s_i is the similarity score of signature limb, and s_j represents the similarity score of j_{th} limb. In our experiments, k_i is 0.5. The details of region-based posture recognition can be found in our previous work [10].

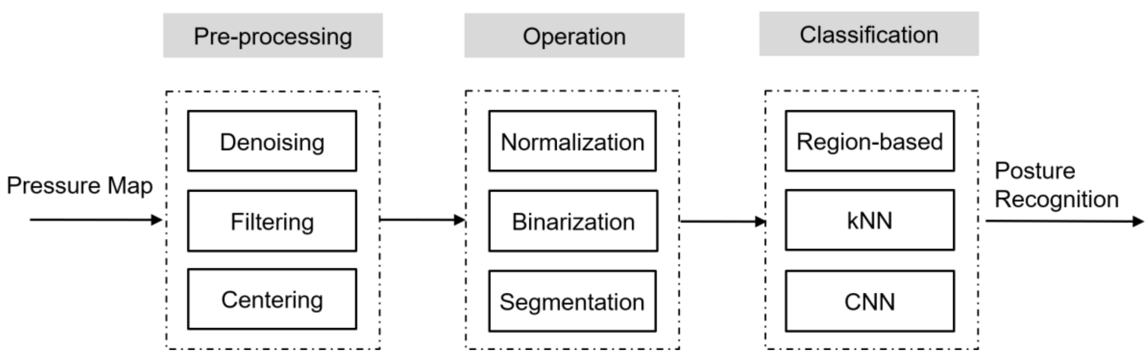


Fig. 3. The framework for posture recognition.

C. Evaluation & Feedback Module

This module includes two major components: condition evaluation and feedback. This module is also one of the two core parts of an automated bed rehabilitation system.

1) Condition Evaluation: In order to assess rehabilitation progress and provide suggestions for next step rehabilitation, a patient's condition should be evaluated. Evaluations only based on posture recognition performance is not accurate and scientific. As shown in Fig. 4, in this work, we propose to comprehensively consider the posture recognition performance, the physical information, and the motor disorder types of patients to conduct condition evaluation.

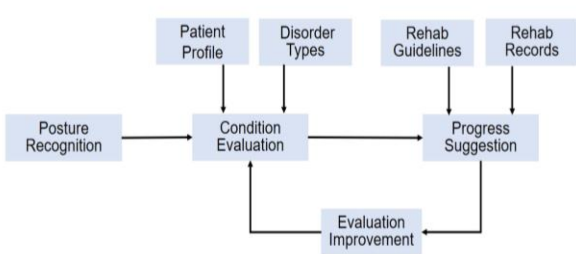


Fig. 4. The diagram of evaluation and feedback module.

2) Progress Suggestion: Once condition evaluation is done, another concern of patients will be what to do next. The proposed system is able to provide detailed suggestions on next step exercise plan. As shown in Fig. 4, these suggestions are made based on condition evaluation results, rehabilitation guidelines and rehabilitation records of patients. The detailed suggestions include what exercise or posture to perform, the repetitions, pace, and intensity of exercises. With these information, patients can correct and adjust their rehabilitation exercises.

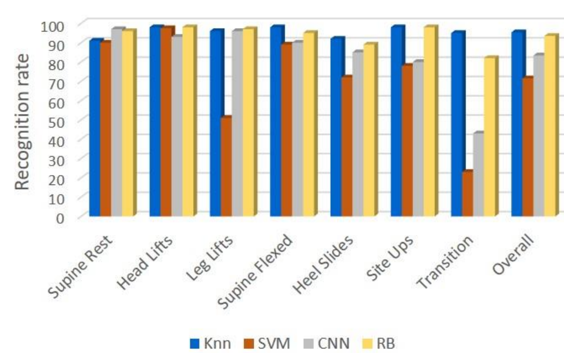
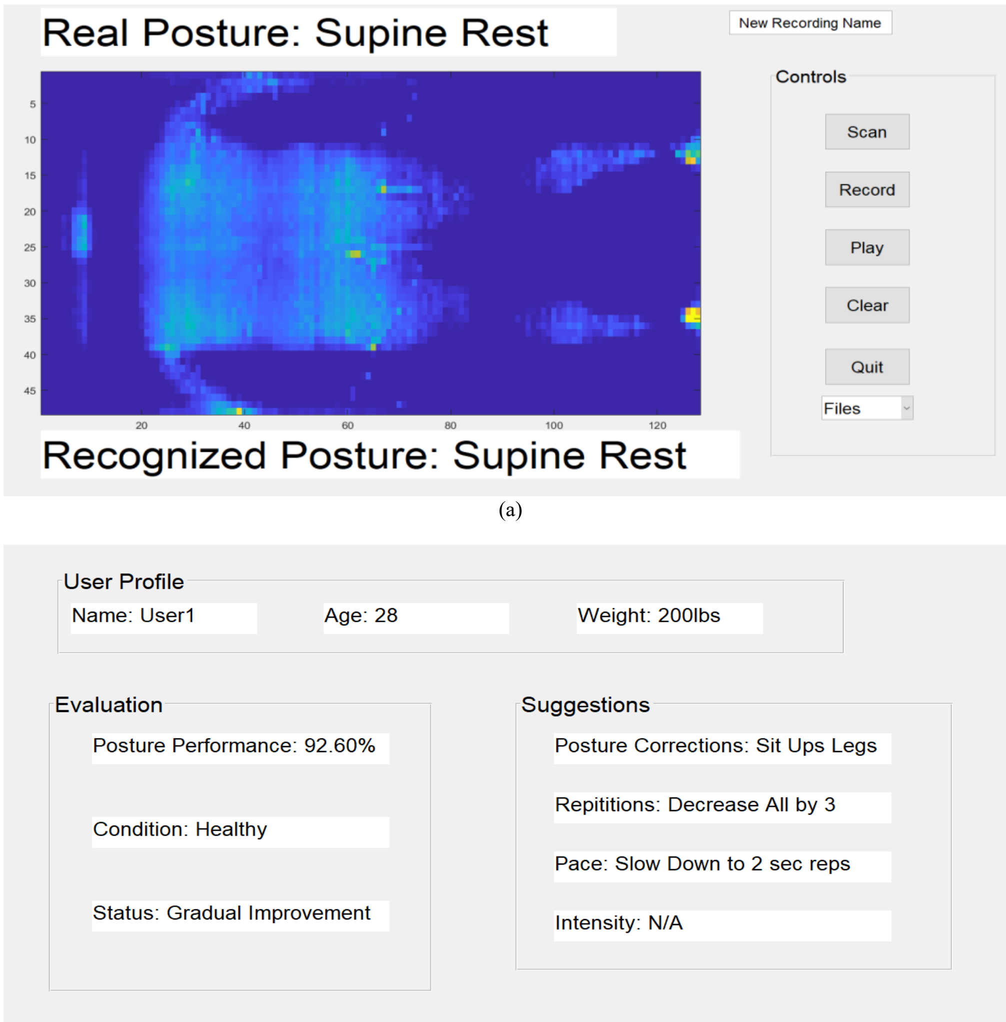


Fig. 5. Posture recognition results.

III. Results

An automated on-bed rehabilitation system would be beneficial to bed-ridden patients both in cost and in making recovery less obtrusive. Preliminary results have shown that the proposed framework is feasible. A sensing module has been implemented to allow data visualization and posture generalization to occur from the pressure map. The posture recognition module has also demonstrated very good performance on various posture recognition. Fig.5 shows the recognition accuracy using various methodologies. The kNN and region-based(RB) obtained a recognition rate higher than 90% while SVM and CNN did not. In addition, CNN was not consistent at all postures especially during transitions. The kNN and GB had the best and competitive performance among these methods. Another aspect needs to be taken into account is that not all postures appear with the same frequency. This allows certain postures to impact the accuracy more than others. Future work will focus on individual posture accuracy to achieve high accuracy regardless of frequency.



(a)

(b)

Fig. 6. Evaluation and feedback interfaces of the proposed automated bed rehabilitation system.

Fig. 6 shows the evaluation and feedback interfaces of the proposed bed rehabilitation system. As demonstrated in Fig. 6(a), it displays posture image and control units. This interface also allows the viewing of the actual posture along with the viewing of the recognized result in the window. This will allow direct verification of results to see how accurate the recognitions are while data is playing back. The software also enables the changing of the algorithms in the background without changing the rest of the functionality.

Fig. 6(b) shows condition evaluation and progress suggestion of a patient with heavy load. The patient profile information is displayed at the top. The evaluation is made based on three factors. Posture performance given as a percentage value. The overall condition of the patient taking into account the posture performance, patient profile and motor disorder type. Finally, there is the status of improvement, which takes into account the recent history of the patient with the system. There is also the suggestions or feedback section. The suggestions are generated based on posture performance, condition evaluation and rehabilitation guidelines. This section provides the detailed information of next step rehabilitation exercises, including the posture adjustment, repetition of exercises, pace, and intensity, which enables the patient to perform a more effective and scientific self-rehabilitation exercise.

IV. Conclution

An automated on-bed physical rehabilitation system is designed and developed. Preliminary results have demonstrated the feasibility and effectiveness of the system. Future work will continue to refine the evaluation and feedback mechanism, enlarge the testing pools, and improve the system integration.

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