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Automated Assessment of Mobility in Bedridden Patients

Stephanie Bennett, *Member, IEEE,* Rafik Goubran, *Fellow, IEEE*, Kenneth Rockwood, and Frank Knoefel.

Abstract— **Immobility in older patients is a costly problem for both patients and healthcare workers. The Hierarchical Assessment of Balance and Mobility (HABAM) is a clinical tool able to assess immobile patients and predict morbidity, yet could become more reliable and informative through automation. This paper proposes an algorithm to automatically determine which of three enacted HABAM scores (associated with bedridden patients) had been performed by volunteers. A laptop was used to gather pressure data from three mats placed on a standard hospital bed frame while five volunteers performed three enactments each. A system of algorithms was created, consisting of three subsystems. The first subsystem used mattress data to calculate individual sensor sums and eliminate the weight of the mattress. The second subsystem established a baseline pressure reading for each volunteer and used percentage change to identify and distinguish between two enactments. The third subsystem used calculated weight distribution ratios to determine if the data represented the remaining enactment. The system was tested for accuracy by inputting the volunteer data and recording the assessment output (a score per data set). The system identified 13 of 15 sets of volunteer data as expected. Examination of these results indicated that the two sets of data were not misidentified; rather, the volunteers had made mistakes in performance. These results suggest that this system of algorithms is effective in distinguishing between the three HABAM score enactments examined here, and emphasizes the potential for pervasive computing to improve traditional healthcare.**

I. Introduction

Functional impairment and impaired mobility have been considered geriatric 'giants' since before 1997 [1],[2]. In older patients, impaired mobility is a complex phenomenon and can often be a sign of underlying disease [3]. Methods of assessing a patient's ability to move have therefore been of considerable interest to health professionals in determining older patients' health. The Hierarchical Assessment of Balance and Mobility (HABAM) is an assessment tool developed to assess, track, and therefore manage patient health by observing patient ability, then allocating a score once per day from hospital admission to discharge [4]. Progressions or declines in patient health are numerically and graphically represented. The HABAM tool is set apart from other mobility assessment tools, as it allows for the assessment of bedridden patients as well as patients who are only mildly functionally impaired [5]. This feature is important, as bedridden patients are often the most frail and unstable, and are therefore in the highest need of close observation and management [6]. Immobile patients are at particular risk for developing pressure ulcers; a geriatric syndrome that has increased in prevalence in the last couple of years [7].

While the HABAM has been shown to be reliable, responsive, sensible, as well as a predictor of adverse outcomes [6],[8], it is not currently used enough by hospital staff to be informative. This is not an uncommon problem in modern hospitals; proportionally, populations are aging at a rapid pace, overloading health resources and staff [9]. The addition of any clinical tool that takes nurses away from patient care is not currently a popular idea. Many hospitals are therefore integrating automated computing into hospital and home environments to help care for increasing numbers of older patients while maintaining the quality of healthcare. The goal of this work is often not only to automate, but to improve current health measurements. Particular to impaired mobility and immobility, much work has been completed with accelerometers or pressure sensors. This is inclusive of: monitoring and detecting sleep patterns [10],[11], monitoring and detecting gait patterns [12],[13], pressure ulcer prevention [14],[15], and 'smart home' environments [16],[17] among other research.

Considering the implications of immobility, the lack of clinical tools developed to monitor it, and the successful use of integrated computing, the automation and integration of HABAM may be an important informative addition to many hospitals. This paper explores a volunteer-based, partial automation of the HABAM tool, focusing on the assessment of in-bed HABAM scores as a precursor to studies in bedridden patients. This work aims to not only automate, but gain insight on small measures of mobility in bedridden patients and explore the possibility of expansion of the HABAM to include more graded measurements of mobility.

II. Methods

A. Equipment and Set-up

The equipment used were: a laptop, a video camera, three pressure sensitive mats manufactured by S4 sensors (formerly Tactex Controls Inc.), and accompanying software. Each pressure sensitive mat is approximately 80cm long, 25cm wide and consists of a 3 (width) by 8 (length)

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Stephanie Bennett and Rafik Goubran are with the Department of Computer and Systems Engineering, Carleton University, 1125 Colonel By Drive, Ottawa ON, K1S 5B6 Canada (corresponding author e-mail: sbennett@sce.carleton.ca).

Kenneth Rockwood is with the Division of Geriatric Medicine at Dalhousie University and the Geriatric Medicine Research, Capital District Health Authority, 1421-5955 Veterans Memorial Lane, Halifax, NS, B3H 2E1 Canada (email: kenneth.rockwood@dal.ca).

Frank Knoefel is with the Department of Family Medicine at the University of Ottawa, and the Bruyère Continuing Care Center, 43 rue Bruyère, Ottawa, ON, K1N 5C8 Canada (email: fknoefel@bruyere.org).

pressure sensor array embedded in polymer foam, then covered in medical grade plastic. An individual sensor is comprised of two optical fibers, a light emitting diode (LED), and an integrating cavity. A sensor measures pressure (in terms of voltage) by sending light from the LED through one optical fiber into the integrating cavity, and measuring the intensity of the light returning from the cavity through the other optical fiber to a photodiode. Light intensity changes as pressure is applied, and each sensor captures this data at sampling rate of 10Hz. Specific details on sensor behavior (such as saturation sensitivity, creep, and hysteresis) is detailed in [18]. The data generated by the mats is sent via Bluetooth to a laptop where it is stored in a comma separated values (csv) file. The video camera was used to document volunteer movements for reference purposes.

The pressure mats were placed on the steel frame of a standard hospital bed, secured, and the accompanying mattress was placed on top of the mats. The hospital bed frame was designed to fold in order to sit a patient up in bed, and so was constructed of four panels: one large panel supporting the back, two small panels at the sacrum, and an intermediate sized panel supporting the legs. Mat placement on the frame was dictated by the construction; each mat was oriented so that the length of the mat spanned the width of the frame. One mat was placed in the middle of each of the larger panels, and the last mat on top of the only panel at the sacrum that was large enough to support it. A schematic of the mats on the bed frame can be seen in Figure 1.

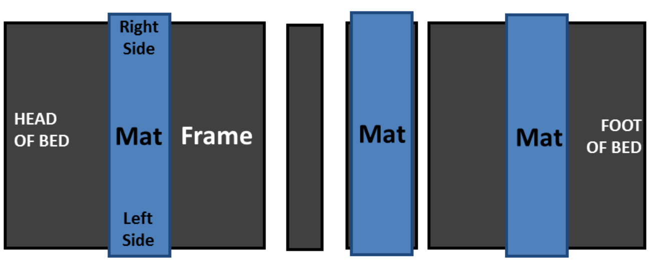

Figure 1. Experimental set-up

B. Experimental Procedure

Data were collected from the mattress alone and five volunteers performing entirely in-bed enactments of HABAM scores. These scores were: a score of 0 for ‘Needs positioning in bed’, a score of 4 for ‘Positions self in bed’, and a score of 7 for ‘Lying-sitting independently’. Each volunteer was asked to lie quietly, without moving, for 5 seconds before every movement. This allowed for the calculation of a baseline pressure reading. After lying quietly, each volunteer performed three separate movements that were enactments of different levels of ability representing bedridden related HABAM scores. These movements are described as follows:

1) Score 0: Needs positioning in bed

‘Needs positioning in bed’ means that the patient is unable to lift supine pressure points off of the bed. These points include under the head, both of the scapulae, both at the sacrum region and both of the heels. This movement was therefore: lie quietly for 5 seconds, then move for approximately 20 seconds attempting to roll to a side of the body, but unable to relieve pressure points in order to do so.

2) Score 4: Positions self in bed

‘Positions self in bed’ means that the patient is able to lift supine pressure points off of the bed in order to re-position the body. This movement was therefore; lie quietly for 5 seconds, then for approximately 20 seconds roll from a supine position onto one side, back to a supine position and continue on the other side. The ‘slow’ rate at which volunteers were to roll was hard to regulate, so the frequency of rolling varied.

3) Score 7: Lying-sitting independently

‘Lying-sitting independently’ means that the patient is able to independently lift their upper body to a sitting position. This movement was therefore; lie quietly for 5 seconds, then over approximately 10 seconds, lift the upper body (allowing the use of elbows and hands) from a lying position into a sitting position. Again, the ‘slow’ pace of volunteers was varied.

C. Data Analysis

Data were examined as individual sensor scores and sums of sensor scores over time. A system of algorithms consisting of 3 main subsystems was designed to correctly identify HABAM score enactments. The first subsystem ‘zero-ed’ data; this effectively eliminated the weight of the mattress from all volunteer performed enactments. This was done by performing the following procedures:

1) Individual sensor data collected of the mattress alone, before each volunteer enactment, was averaged ($(\sum mat_{sensor})/frames$). This gave the average mattress pressure at each sensor. These average pressures were subtracted from respective sensor data for every enactment by each volunteer ($rawdata_{sensor}(t)$). This calculation can be seen in (1), which was re-calculated for each volunteer. The variable *frames*, refers to the number of data frames captured of the mattress alone.

$$zeroed_{sensor}(t) = rawdata_{sensor}(t) - (\sum mat_{sensor})/frames \quad (1)$$

Subsystem 2 determined if the volunteer was enacting a score of 0, ‘Needs positioning in bed’, or a score of 4, ‘Positions self in bed’. For the purposes of this study, this subsystem considered only the middle mat at the sacrum region, and performed the following procedures:

1) The data were first separated in two groups; the left side of the mat, and the right side of the mat. Each group included 12 sensors. For each sensor in each group, an average of the first 30 frames (3 seconds) of each enactment by each volunteer was calculated. This gave a baseline pressure reading for a subject on the mats ($base_{sensor}(t)$).

2) For every sensor, the percentage change over time from baseline was calculated. This change was considered as either a percentage increase or a percentage decrease as indicated in (2) and (3) below, which were calculated for each enactment. The variable $zeroed_{sensor}(t)$ is the zeroed data from subsystem 1, $base_{sensor}(t)$ is the baseline pressure reading, $pinc_{sensor}(t)$ is percentage increase, and $pdec_{sensor}(t)$ is percentage decrease.

$$pinc_{sensor}(t) = ||zeroed_{sensor}(t) - base_{sensor}(t)|| \,/\, base_{sensor}(t) \quad (2)$$

$$pdec_{sensor}(t) = -||zeroed_{sensor}(t) - base_{sensor}(t)|| \,/\, base_{sensor}(t) \quad (3)$$

3) Individual sensor data was then filtered via a moving average filter with a window of W=5.

4) Points in time at which a sensor recorded a percentage decrease of -0.95 or less were recorded, along with the sensor location in the mat, and the baseline sensor value. A percentage decrease of -1.0 meant that the original pressure had been relieved; however -0.95 was used here to allow for a small amount of error which accounted for the effect of the mattress (0.05).

5) Instances during which at least two sensors had simultaneously dropped below a percentage change of -0.95, were identified. These results were separated by the left and right grouping. The algorithm then conditionally separated score 0 enactments from score 4; if no double incidences of sensor percentage changes dropping below -0.95 occurred, then the enactment was of score 0, and was recorded as such.

Subsystem 3 determined whether not a volunteer was enacting a score of 7, 'Lying-sitting independently'. This subsystem performed the following procedures:

6) For each volunteer, enactment and point in time, data from sensors in the top mat were summed. This was also done for the bottom mat. Summed data from the top mat was divided by summed data from the bottom mat to get a ratio of proportional distribution of the body over these two mats. The equation for this can be seen in (4), where the subscripts *TOPsensor* and *BOTTOMsensor* refer to the respective 24 sensors in each of the bottom and top mats.

$$ratio(t) = \sum zeroed_{TOPsensor}(t) \,/\, \sum zeroed_{BOTTOMsensor}(t) \quad (4)$$

7) A unique feature of the lying to sitting movement is that the calculated pressure ratio is over 1.0 when a subject is lying, and drops to below 1.0 when the subject is sitting. This condition was applied to all data generated by volunteers, where if true, the enactment was considered to be of score 7.

III. Results

Subsystem 2 determined if the enactment was either of score 0: needs positioning in bed, or score 4: can position self in bed. This was done by calculating percentage increase and percentage decrease, then identifying incidences below a threshold 0.95 percentage decrease. An example of simultaneous pressure relief from three sensors underneath the left hip, for one volunteer performing an enactment of score 4 can be seen in Fig. 2. This triple incidence occurs at frame 107 and is highlighted with an arrow. The location of the relieved sensors (highlighted in blue) on the left side (highlighted in yellow) of the middle mat can be seen in Fig. 3. This mat is oriented on the bed frame as in Fig. 1. The way this subsystem was designed meant it was capable of determining if a person had rolled to one side, the extent to which they did so, which side and at what time. This subsystem could be further developed to include these measures in assessments.

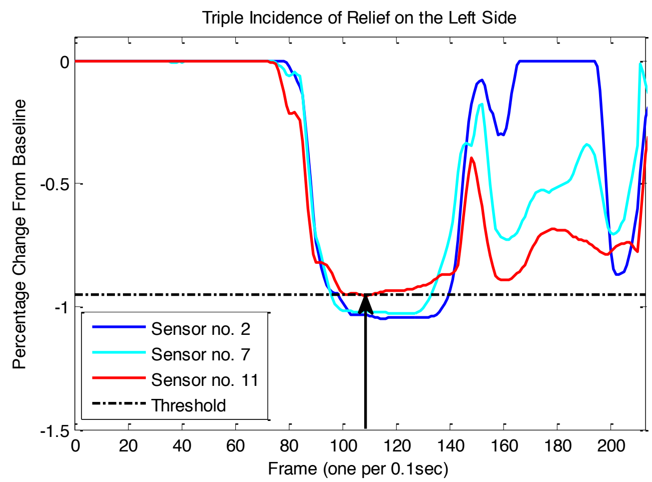

Figure 2. Relief of three sensors under the left hip during enactment of score 4.

1	**2**	3	4	1	2	3	4
5	6	**7**	8	5	6	7	8
9	10	**11**	12	9	10	11	12

Figure 3. Location of relieved sensors in the mat.

Subsystem 3 determined if the enactment was of score 7: lying-sitting. This was done by calculating the sums, then ratios of the top mat and the bottom mat at every point in time, respectively. An example of this feature can be seen in Fig. 4, where the unique characteristic identifying score 7 is illustrated; that the ratio begins at a value above 1.0 and drops to below 1.0.

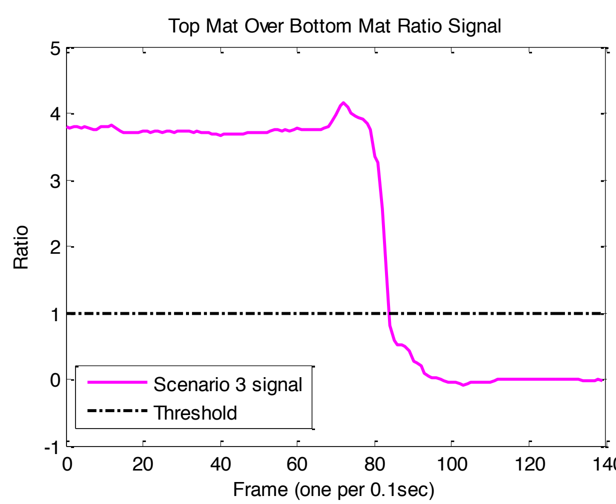

Figure 4. Top over bottom mat ratio for scenario 3.

Overall results of the system can be observed in Table I. The system assessed all but two enactments as expected. Upon further inspection of the data and video footage, it appeared as though the system did not assess these enactments incorrectly. Participant 1 did not perform the motion exactly as instructed (a pressure point was slightly lifted in an enactment of score 0) and Participant 5 began exiting the bed before data collection was ceased.

TABLE I
ENACTMENTS OF SCORES AND RESULTING SYSTEM ASSESSMENT

Participant	**HABAM Score Enactment**		
	Score 0	**Score 4**	**Score 7**
1	4	4	7
2	0	4	7
3	0	4	7
4	0	4	7
5	4	4	7

IV. CONCLUSION

This paper aimed to automate a volunteer-based, partial HABAM assessment. Five volunteers performed three enactments each, on a standard hospital bed while pressure data was gathered from pressure mats underneath a hospital mattress. A system of algorithms was devised and tested with 15 volunteer data sets, each representing one of three HABAM scores. Examination of the results indicated that this system is capable of determining between the three HABAM score enactments examined in this paper.

The pressure mats used are capable of very fine measures of pressure and this system was designed with the intention of expansion through continued research, so within each of the subsystems described are areas of further examination. For example, subsystem 1 was designed with the intention of further development to identify and distinguish between a subject in a sitting or lying position. Subsystem 2 was designed for expansion to include examination of pressure points and associated patterns underneath a subject during HABAM enactments. The HABAM tool currently only assesses whether or not a patient can lift a pressure point, but the extent to which a patient can or cannot relieve these points can be explored and may be clinically meaningful.

An interesting result found in this paper, was that two enactments were not assessed as expected. Examination of data revealed that the system had not assessed incorrectly, rather, the mats had captured an instance of pressure relief that went unnoticed. This result emphasizes the significance of ubiquitous computing in applications such as the HABAM, as data immeasurable to the eye is captured and recorded. Furthermore, this system, with relative engineering simplicity, was able to better assess HABAM scores than an observing researcher. This supports the idea that automation of the HABAM tool may inform the tool itself, and introduce finer, clinically meaningful measures of immobility.

With the management of mobility progressions and declines in older adults often being overlooked, the number of geriatric patients increasing in an aging population, and the successful implementation of pressure sensing devices in other mobility related applications, the automation of HABAM could not only ensure consistent, reliable assessments and expand upon our knowledge of movement in the immobile, but could also emphasize the importance of pervasive computing in the assessment and tracking of immobility.

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