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Continuous Weight Monitoring System for ICU Beds using Air-filled Mattresses/Pads: A Proof of Concept

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Abstract— **Fluctuations in body fluids can have adverse effects such as dehydration, swelling and related pathologies due to low maintenance of homeostasis. The risk increases if the person is critically ill and bed-ridden. Changes in body weight in short intervals is the primary indicator for body fluid imbalances. Clinical practice involves the use of a dedicated weighing scale/lift scale, detachable/built-in units of weighing scale on the legs of hospital beds and integrated bed scales. These methods have limited mobility and usability in a clinical setting or higher cost. We propose a novel sensing module integrated with air-filled mattress for monitoring human body weight at periodic intervals. The method uses the air pressure of a mattress as a measure of changes in weight. The design was made modular so that it can be easily coupled into any hospital beds. A linear fit with R^2=0.98 and R^2 = 0.99 was obtained respectively for an air-filled pillow and air-filled mattress with the coefficient of variance of 5% to 9%. Initial experiments are performed for an air pillow, and later extended to adult size air filled mattress.**

Keywords—body weight; body fluids; weight measurement; pressure sensor;

I. Introduction

Human body weight is an essential marker of the general wellness of a person and has a strong clinical relevance. The body weight, as well as the change in the weight, is especially relevant in critically ill patients admitted into Intensive Care Units (ICUs), as it's a direct indicator of the fluid balance effectiveness as well as overall health of the patient. Body fluids account for 60% of a person's body weight [1]. Total body fluid volume fluctuates by less than 1%, and fluid intake must be balanced by fluid loss in a healthy person. A 5-10% fluctuation in fluid volume can have adverse effects such as dehydration, swelling and related pathologies due to low maintenance of homeostasis, more prominent in the elderly population [2]. The renal system of our human body undertakes the function of balancing the fluids and maintain our dry weight, preventing dehydration [3]. Patients with kidney failures or renal disorders, often a consequence of diabetics will not be able to regulate the body's fluid balance and will result in edema or swelling and related pathologies. Such patients are required to undergo dialysis to remove excess body fluids (typically 2 - 10 kg of fluid needs to be removed) to maintain their dry weight [4]. However, accurate and periodic weight measurement is one of the ways to assess the fluid balance [5] and often difficult in ICUs when the patient is bed-ridden or immobile. The common clinical practice involves the use of a dedicated weighing scale, which requires the patient to be moved from the bed for measurement, which is not only inconvenient but even clinically ill-advised and unethical in the case of critically ill patients. There exists a need to periodically monitor changes in body weight for detecting imbalances in body fluids for dialysis treatment [6], for detecting complications from an intravenous fluids (IV) therapy [7] and as a measure of nutrition status [8]. Fluctuating body weight dynamics is associated with the low maintenance of body hemostasis resulting in declining health in older adults [9]. An accurate and distributed weight measurement periodically will reduce morbidity and mortality especially in elderly and bedridden patients [10].

Popular commercial methods to measure the body weight of bedridden patients that exist today are based on strain gauge-based load cell measurement devices. These can be in the form of lift scale or a roll-on scale, where the bed carrying the patient is rolled over the weighing scale, i.e. fixed at some part of the building. The other types include a detachable unit or built-in units (of load cells) on the load-bearing mechanical support structure of the hospital bed (cot). The built-in units of load cells under the load-bearing structures will add to the production cost of hospital cots, making it unaffordable to many public health care centres. The detachable units, which must be placed beneath each leg of the cot as and when required, is inconvenient to set up and suffers from usability issues in a clinical setting. The addition of the structural weight of the cot along with the patient weight in such systems forces an over-design of the load cells used, to ensure high accuracy at their lower ranges of operation, which also tends to increase the cost and size of the measurement device [11]. Propagation of errors and failures of any single unit are inherent problems to any multi-sensor measurement system. Typically, loadcells are subjected to dynamic changes of measurement and that too for a short duration of time (2-3 minutes at most). So, when popular methods involving loadcells are used, there is a chance to generate creep in the measurement data, reducing accuracy or permanently damaging the sensors [12]. Hence there exists a need for a simple modular solution to this problem of periodic weight measurement in hospital beds, especially in an ICU.

Some of the exploratory approaches for measuring body weight without the use of loadcells are limited to works in image processing based on body surface area and elliptical tube volume [13]. Another work was based on fiber optic sensor [14], and design of a palmer pressure sensor based on air channels [15].

In this paper, we propose a sensing module, based on an air-filled pillow and air-filled mattress, both attached to a pressure sensor. The body weight changes are tracked in terms of the change in pressure signal generated. Though the importance was highlighted for infants, the same concept of weight monitoring system can be expanded to adults as well which is explored by the air-filled mattress design.

II. MEASUREMENT SYSTEM

The patient weight monitoring system was developed for two different application scenarios: the air-filled pillow design for use with infants and the air-filled mattress for use with bedridden patients. Both the systems utilize an air pressure sensor to measure the weight being applied. The overall system architecture is illustrated in Fig. 1.

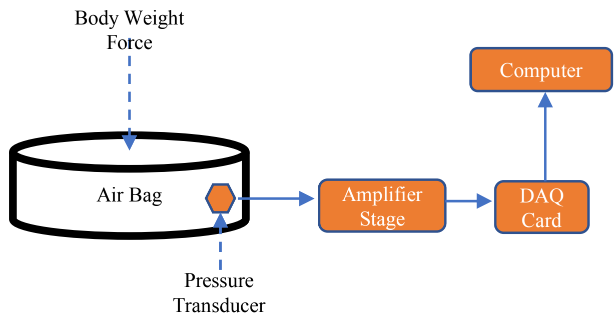


Figure 1. Overall system architecture, applicable to both designs: air-pillow and air-mattress.

A. *Principle*

According to Boyle's law, at constant temperature and for a given mass of air and volume V_0 within a structure, the change in volume and pressure, as a result of the applied load on it, is given by the relation

$$P_0V_0 = P_1V_1 = K \quad (1)$$

where P_0,V_0, P_1,V_1 are initial pressure, initial volume, final pressure and final volume respectively. K is an arbitrary constant. The changes in pressure, i.e. ΔP is detected by the pressure transducer, which can be calibrated to the applied weight (load).

B. *Design of Air- filled Pillow System*

This design includes air-filled pillow of dimension 27 cm x 37 cm x 10 cm, attached to a pressure transducer (NXP - MPXV5100DP) through plastic tubing. The pressure transducer had a built-in amplifier, and the output voltage was directly fed to the data acquisition card (National Instruments (NI) 6002 DAQ) at 1kS/s sampling rate. The raw data was processed, and algorithms were developed in NI's LabVIEW® platform, on a laptop running on Microsoft® Windows® 10 The pillow was inflated using a hand pump. This prototype

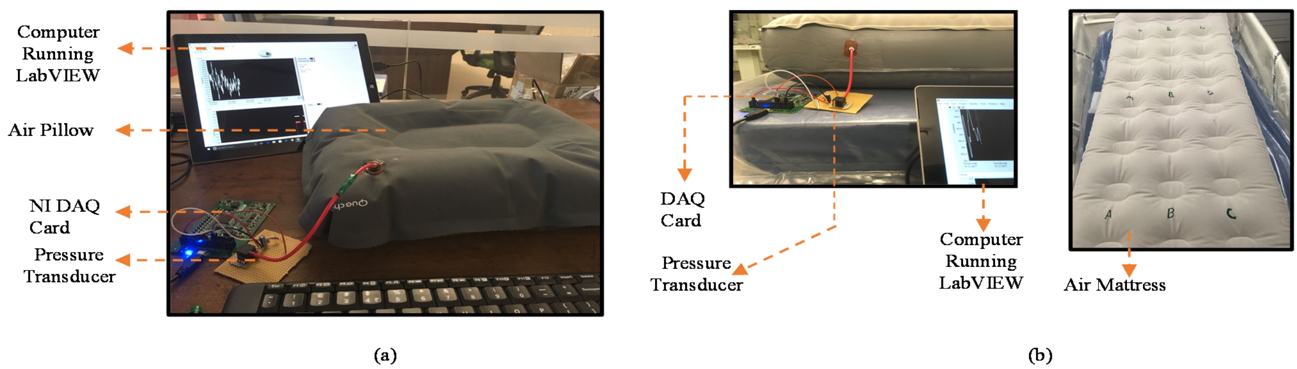
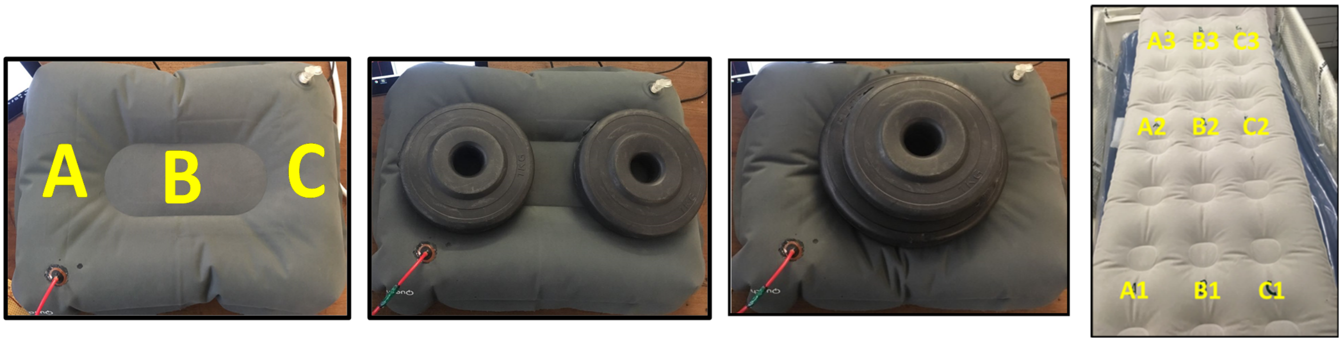


Figure 2 (a) Hardware experimental setup for air-filled pillow design, (b) hardware experimental setup for air-filled mattress design



(a) (b) (c) (d)

Figure 3. (a) Three locations identified on air-pillow for distributed weight placement, (b) weights kept at locations A and C, (c) weight kept at BB, (d) nine locations identified on the air-mattress

represented a lumped sensor model as shown in Fig. 2(a). This design is ideal for measuring the weight of an infant. The infant is placed on the pillow, and the weight can be monitored continuously with minimal interventions.

C. Design of Air-filled Mattress System

This design is an expanded version of the previous one. The air pillow is now replaced by an air-filled mattress of dimension 190 cm x 70 cm x 60 cm with all other data acquisition hardware remaining the same as earlier. The second design explores how a single large model could replace the need of several individual sensing units, as shown in Fig. 2(b), which would be typical use case for measuring the weight of adults.

III. Experimental Verification

The objectives include, (a) determining the relationship between pressure change and applied weight on air-filled pillow and mattress, (b) determining the repeatability in measurement, (c) to study the effect of uniform and non-uniform distribution of applied weight.

A. Pressure Response in Air-filled Pillow

Standard weights of known values (1-8 kg) are placed on the air-filled pillow, and the pressure response is obtained. The pressure response for a pressure transducer is expected to be of the form,

$$F = c_1(P - P_0)^n + c_2 \quad (2)$$

where P is the measured output pressure, P_0 is the initial pressure or offset, c_1 and c_2 are constants. and F is the applied force. The pressure difference (P-P_0), is often used throughout this paper as the measurement quantity of interest.

B. Effect of Distributed Weights on Air-filled Pillow

The standard weights are placed on three different points on the pillow as shown in Fig. 3(a) to check for variations in pressure values with respect to location.

Standard weights are also redistributed among the different locations to check for variability in pressure, i.e. for e.g. A 2 kg weight is kept as 1 kg in location A and 1 kg in location C apart from placing 2 kg at each location individually as shown in Fig. 3(b) and Fig. 3(c).

C. Effect of Initial Pressure on Air-filled Pillow

The initial pressure inside the air-filled pillow was varied from 0 kPa to 2.5 kPa using a hand pump to identify optimal values of initial pressure that would give higher sensitivity.

D. Pressure Response in Air-filled mattress

A very similar procedure was carried out to obtain the pressure response in an air-filled mattress subjected to various loading of weights. For testing variability to locations, nine different spots were chosen on the mattress as shown in Fig 3(d). on which weights were placed, and the corresponding step response is noted.

IV. Results and Discussions

A. Pressure Response from Air-filled Pillow

There exists a linear relationship between pressure difference and applied weights with $R^2 = 0.98$ for the air-filled pillow shown in Fig. 4(a), empirically given by the curve fit relation,

$$\Delta P = 0.168W - 0.018 \quad (3)$$

where W is the applied weight ranging from 1 kg to 8 kg, and ΔP is the pressure difference measured.

By referring to Fig. 3(b), Fig. 3(c) and Fig. 4(b) even at individual locations on the pillow (A, B & C) there is a linear relationship between pressure difference and weight. The pressure difference values are the same at locations A & C. At

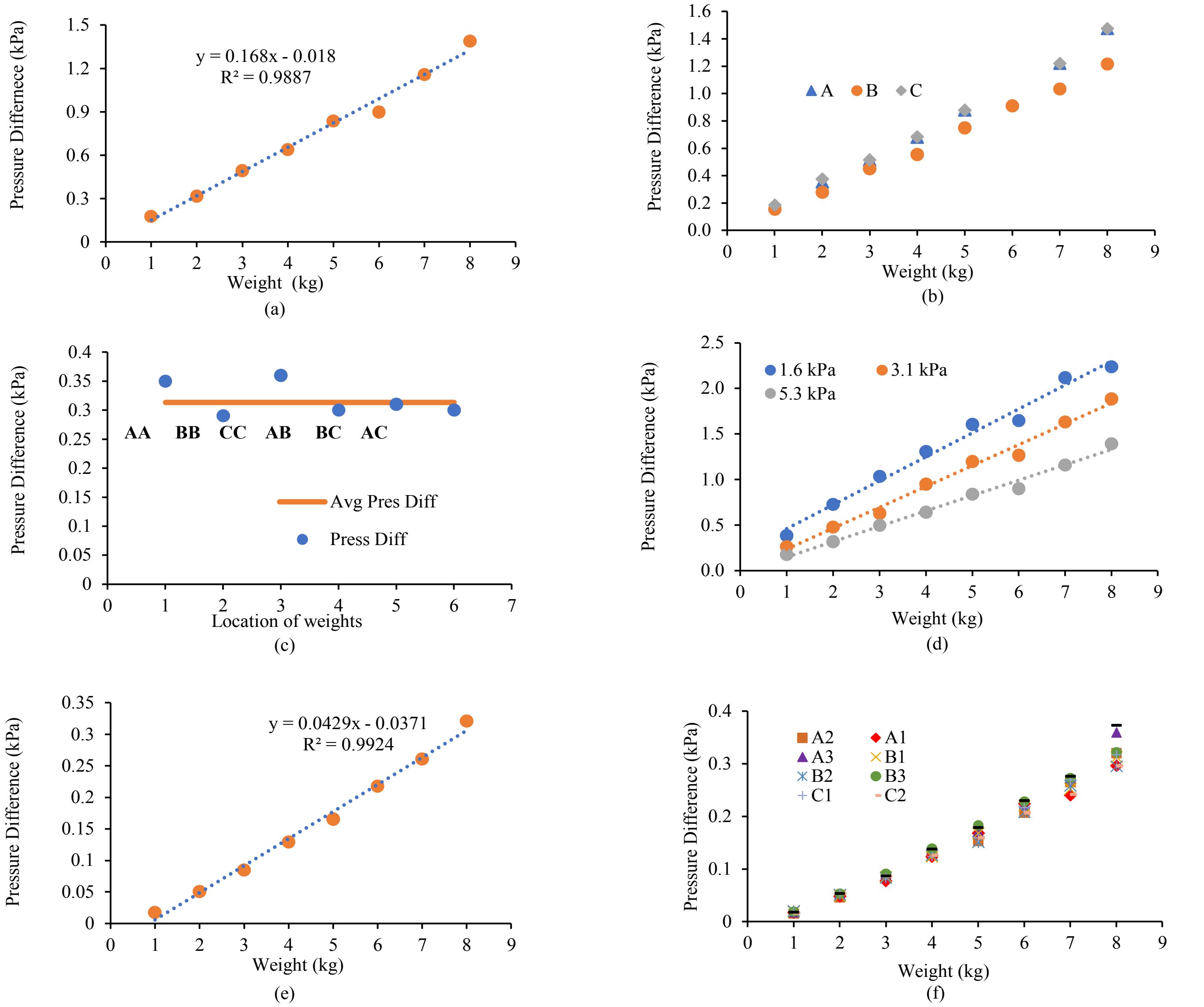


Figure 4. (a) Linear relation between pressure and weight for air-pillow, (b) effect of weight placement at three different locations on air-pillow a, (c) A 2 kg weight is placed in distributed arrangement, (also refer to Fig.2.), (d) influence of initial pressure,(e) linear relation between pressure and weight on air-mattress, (f) effect of weight placement at nine different locations on air mattress.

location B, the values are slightly lower. This can be attributed to the change in contact area between the two situations.

B. Effect of Distributed Weights on Air-filled Pillow

It was observed that for a particular weight value (say 2 kg), when weights are placed distributed (1 kg and 1 kg), there is variation in the pressure difference values. This is illustrated in Fig. 4(c). In the figure, AA corresponds to keeping two units of the 1 kg block at position A, and AB corresponds to keeping 1 kg at A and another 1 kg. Variation in pressure could be due to air movement inside in all directions and changes in contact area between weights and pillow.

C. Effect of Initial Pressure on Air-filled Pillow

For a given initial pressure, the rate of change of pressure difference increases as the initial pressure decreases, i.e. a maximum sensitivity was achieved when the initial pressure was minimum, as shown in Fig. 4(d). Hence, it is important to maintain uniform initial pressure which is difficult, due to inherent challenges associated with any air-filled system, which is discussed in the limitations section of this paper.

D. Pressure Response on Air-filled Mattress

There exists a linear relationship between pressure difference and applied weights with $R^2 = 0.99$ for the air-filled pillow, empirically given by the relation shown in Fig. 4(e).

$$\Delta P = 0.0429x - 0.0371 \qquad (4)$$

where x is the applied weight ranging from 1 kg to 8 kg, and ΔP is the pressure difference measured.

The linear relationship still holds good between pressure difference and weights for the air-filled mattress, considering average values of all the nine different locations, illustrated in Fig.4(f). For lower weight values, location did not have any effect on the pressure difference values. It was observed that for higher weights, there is higher (4% - 9%) coefficient of variance (CoV) over the entire range of weights. For a given weight, there is little variation (5% CoV), due to the location of the weight on the mattress (provided entire weight acts at that location). If the weights are distributed at different locations, the average pressure values are lower compared to undistributed loads. The CoV of pressure values in the case of distributed loads is around 5%.

V. LIMITATIONS

Air filled pillow/mattress seemed to be the cheapest solution, but the system has some practical difficulties. Leakage of air is a major issue and its effect is more pronounced in larger mattress compared to the air pillow. Outside temperature also influences the rate at which air leaks. Change of initial pressure of the system makes repeatability study and calibration difficult. This can potentially be overcome with an active system where the initial pressure is maintained the same by a control mechanism. The present system may also generate creep and drift, and this can be improved in the material selection of future designs. The mattress is not constrained, i.e. it is free to move in all directions. Hence, incompressible liquid-filled elastic tubes with feedback control to regulate the pressure to optimum ranges that gives maximum sensitivity was identified as a replacement of the air-filled pillow/mattress for continued research and such a system is under development by our group to address the above limitations.

VI. CONCLUSION

In this work, we have presented a proof of concept for periodic monitoring of human body weight of infants and adults on hospital beds. This method is based on a pressure response from the air-filled mattress or a pillow and can be easily integrated underneath any hospital bed. This study was restricted to small ranges of weights as a proof of concept design and it was found that there exists a linear relationship between pressure response and applied weight with $R^2 = 0.98$ and $R^2 = 0.99$ for air-filled pillow and mattress respectively. There is a CoV of 5% to 9% among the entire range of applied weight from 1 kg to 8 kg. This system provides a baseline study which could potentially help in developing a weight monitoring system for larger capacity, sensitivity and better repeatability. Our research is continuing to extend this concept with better accuracy focusing on neo-natal health using an active system.

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