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A Novel Approach to Prevent Pressure Ulcer for a Medical Bed using Body Pressure Sensors

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Abstract

Despite numerous air mattresses marketed to prevent Pressure Ulcers (PU), none have fully succeeded due to residual pressure surpassing critical levels. We introduces an innovative medical bed system aiming at complete PU prevention. This system employs a unique 4-bar link mechanism, moving keys up and down to manage body pressure. Each of the 17 keys integrates a sensor controller, reading pressure from 10 sensors. By regulating motor input, we maintain body pressure below critical levels. Keys are equipped with a servo drive and sensor controller, linked to the main controller via two CAN series. Using fuzzy or PI/IP controllers, we adjust keys to minimize total error, dispersing body pressure and ensuring comfort. In case of controller failure, keys alternate swiftly, preventing ulcer development. Through experimental tests under varied conditions, the fuzzy controller with tailored membership functions demonstrated swift performance. PI control showed rapid convergence, while IP control exhibited slower convergence and oscillations near zero error. Our specialized medical robot bed, incorporating 4-bar links and pressure sensors, underwent testing with three controllers—fuzzy, PI, and IP—showcasing their effectiveness in keeping body pressure below critical ulcer levels. Experimental results validate the proposed approach's efficacy, indicating potential for complete PU prevention.

Keywords: *Pressure Ulcer Prevention; Medical Bed; Pressure Sensor; Fuzzy Control*

1. Introduction

The main cause of ulcer is the factor: body pressure x duration time, and when it exceeds the threshold pressure value of 32mmHg, ulcers begin to progress, and if the long-time elapses in this state, ulcer can occur [1]. The PU can affect any part of the body that's put under pressure. They're most common on bony parts of the body, such as the heels, elbows, hips and base of the spine. Moore Z. et al (2017) described the pathophysiology of pressure ulcer development [2]. Many pneumatic mattresses for prevention ulcer are also

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on the market, but the residual body pressure exceeds the critical body pressure of 32mmHg, so complete ulcer prevention has not been achieved yet [3]. However, in the case of a keyboard type bed, ulcer can be theoretically prevented by moving the keyboard up and down: zero pressure by moving the keys down or by adjusting the duration time to be within a critical time when the keys are raised [4-6]. In principle, it is well known that the posture change time of a body to prevent PU needs to be within two hours, and the shorter the better, which changes periodically the contact area of pressure. This belongs to the duration time control of body pressure. It has been suggested that alternating key movement every 10 minutes for an automatic bed equipped with the keyboard [6-7]. This method has the advantage of open-loop control not requiring a body pressure sensor and the pressure is zero when the key is lowered. However, it has a disadvantage that comfortability is not good when the key lifts alternatively and the body pressure can rather increase when the key is lifted. In this work, we present two stage control approach to prevent ulcer. The first stage is the control to suppress body pressure under the critical one using the fuzzy control or PI/IP control while holding the comfortability of a body, and the second one is alternating key movement within a short time, which begins when the first stage control is failed. This belongs to time control. The experimental result is shown to verify the effectiveness and validity of the proposed approach.

We developed the customized pressure sensor to measure the distribution of body pressure sensor and designed the special four bar link mechanism without inversion problem while moving the keyboard of the bed up and down. We controlled the body pressure not to exceed the critical one which can cause PU. Several control methods were tested and compared.

2. The Developed System

2.1 Mechanical Part

Figure. 1 shows the appearance of the developed bed which is mainly divided into two parts. The upper part is the keyboard mattress consisting of 17 keys which are the modified 4 bar mechanisms and the lower one is the common electric bed platform. The keyboard consists of the parallel link mechanism made to perform a four-bar driven movement. The 4 bar mechanism inherently has a phase inversion problem, so to solve this problem, a phase offset has been placed. Fig. 1 shows a keyboard-structured bed equipped with 17 such mechanisms, which is an electrically powered robot bed for PU prevention.

Figure 1. The developed medical bed

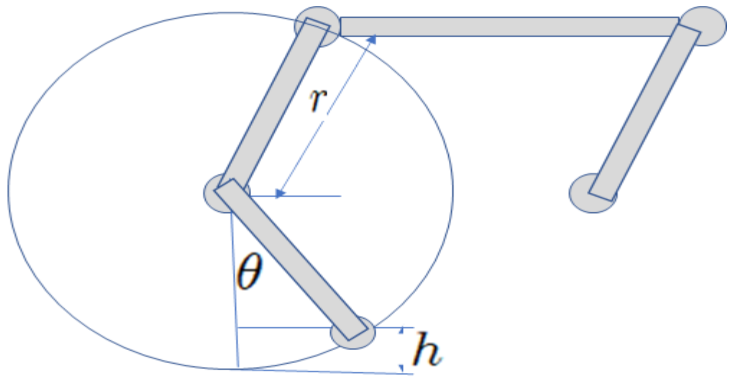


Figure 2. The movement of the 4 bar link mechanism

Figure. 2 shows the movement of the 4 bar mechanism of a key. If the height h of a keyboard, with a radius r and an angle θ, can be described as follows.

$$h=r(1-\cos\theta) \quad (1)$$
$$\theta=\arccos(1-h/r) \quad (2)$$

2.2. The Control System Hardware

The main controller is divided into several parts: user interface part, motion controller one, and host interface one. And they are connected by 2 CANs (Car Area Networks) which communicate with multiple motion servo controllers and multiple sensor controllers, respectively. Sensor signal processing parts are also included. The developed medical bed consists of N keys, and each key is equipped with a BLDC(Brushless DC) motor that drives them. Each motor is equipped with a servo driver to enable the position and speed control of a keyboard. The main controller has two CAN ports, one is connected to N motor driver controllers in series, and the other to the body pressure sensor controllers (Figure. 3). The sensor controller on a key gathers the sensor information and sends it to the main controller via CAN.

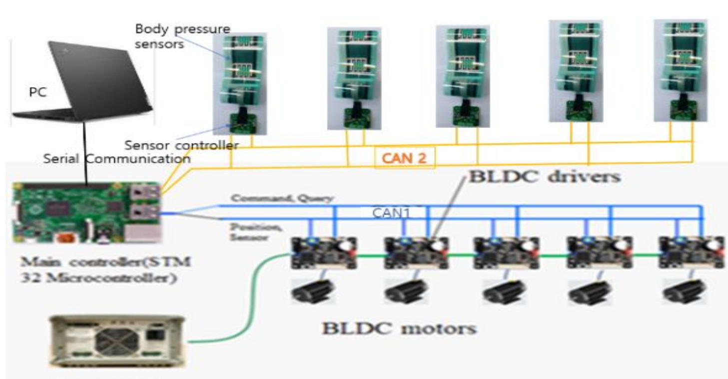


Figure 3. The overall structure of the control system

The main controller commands the height value of each key to the N motor servo drivers as an angle through CAN communication and reads the actual height value from the servo drivers. Similarly, the M body pressure sensor values on each key are read from the sensor controller and are transmitted to the main controller via CAN. The larger the number NM of sensor values, the greater the resolution of the body pressure map. N and M are limited for physical and practical reasons, and they are set to 17 and 10, respectively like as Figure. 4.

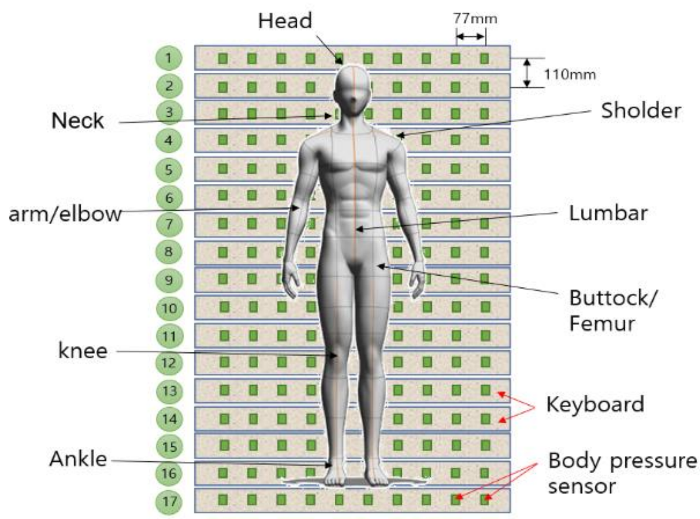


Figure 4. The regional division of the keyboard mattress

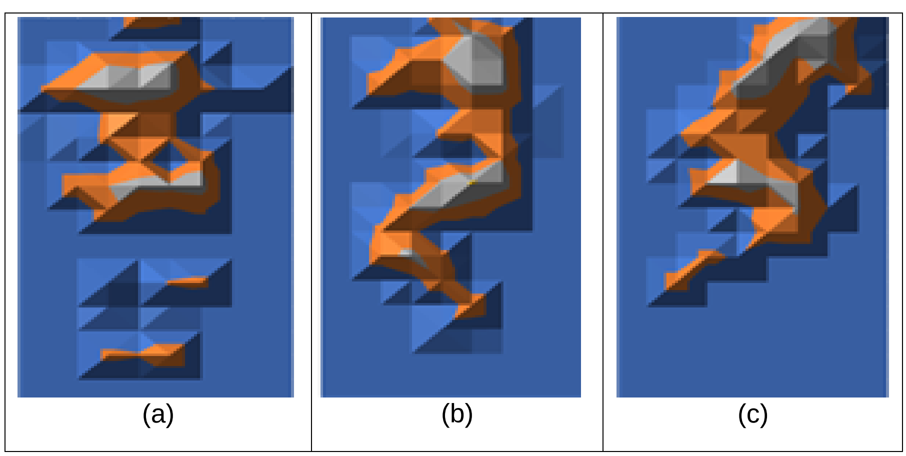


Figure 5. An illustration of body pressure map

(a) supine (b)right (c)left lying position

: The body pressure map is the distribution of the total pressure collected from the sensors

3. The Body Pressure Control

3.1. Problem Description

To calculate error e_i, we will consider some variables like the critical ulcer pressure (P_cu), the set pressure value (P_sv), maximum pressure of the key i as (P_mi), the height of the keyboard i as (h_i), the error between 〖(P〗_cu) and (P_mi) as e_i and u_i (=h_i) as the height of a key or position input.

We can calculate the error e_i by the following equation:

$$e_i = min(p_{mi} - p_{cu}, 0), i = 1,2, \dots N \quad (3)$$

The RMS (Root Mean Square) error can be computed as:

$$e_{RMS} = \sqrt{\frac{\sum_{i=1}^{N} {e_i}^2}{N}}, i = 1,2, \dots N \quad (4)$$

Where, N is the number of keys. The maximum pressure P_mi of the i-th key is defined as:

$$P_{mi} = max\ p_{ij}, j = 1,2, \dots M \quad (5)$$

where, M is the number of pressure sensors in a key. The pressure ratio (R_(i)) for each key i is computed as:

$$R_i = \frac{\sum_{j=1}^{M} P_{ij}}{\sum_{i=1}^{N} \sum_{j=1}^{M} P_{ij}} \quad (6)$$

3.2. Fuzzy Logic Controller

A fuzzy logic system (FLS) is the nonlinear mapping of an input data set to scalar output data [8, 9]. An FLS consists of four main parts: fuzzifier, rules, inference engine, and de-fuzzifier. The fuzzy logic process is as follows: Firstly, a crisp set of input data are gathered and converted to a fuzzy set using linguistic variables, linguistic terms and membership functions. This step is known as fuzzification. Afterwards, an inference is made based on a set of rules. Lastly, during the defuzzification step, the resulting fuzzy output is mapped to a crisp output using the membership functions. In this study, we employ a fuzzy controller to regulate the maximum pressure error of a single keyboard to be under critical ulcer pressure. Figure. 6 shows the architect of the fuzzy controller. The body pressure sensors are attached to the keyboard whose height is adjusted by a fuzzy controller.

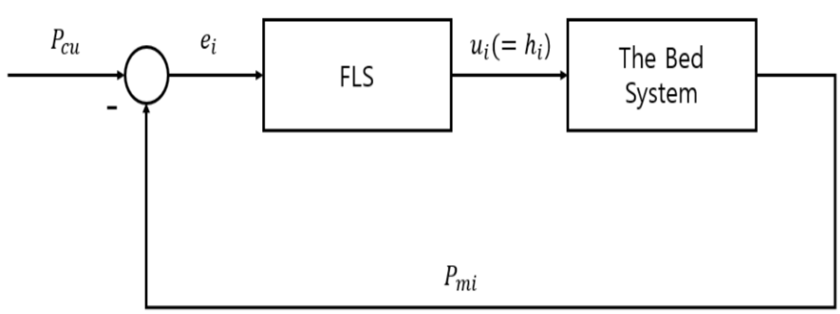
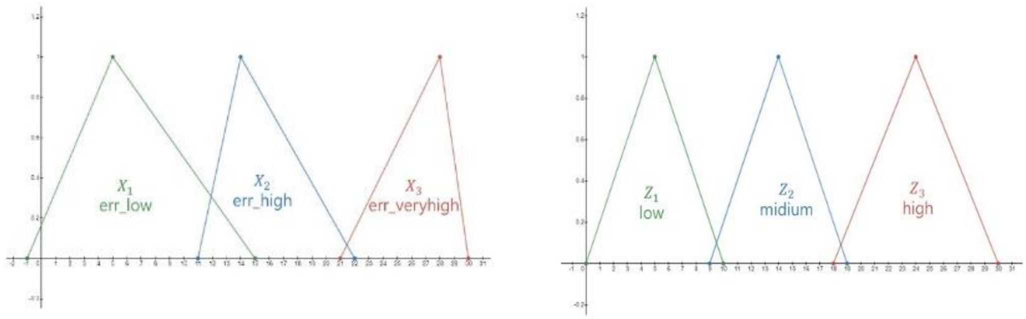


Figure 6. The fuzzy logic controller

The error (e_i) is the input to the controller, and the keyboard height (h_i) is the output to the controller. The membership functions to the input and output are shown in Fig. 7 (a) and (b), respectively. The shape of the membership function is designed through experiments. The RMS error by per cent can be calculated from equation (7)

$$The\ e_{ki} = \frac{\sqrt{Min(p_{cu} - p_{mi}, 0)^2}}{p_{cu}} \times 100,\ i=1,\ 2,\ \dots,\ N \quad (7)$$



(a) fuzzy Input (b) fuzzy Output

Figure 7. Fuzzy input/output membership functions

The fuzzy controller has inferred by the Max-Min method. The fuzzy rules are shown in Table1. Here, X is the error variable, Z is the height variation, respectively.

Table 1. Fuzzy Rules

Rule	**If-Then**
R_1	If X is X_1, Then Z is Z_1
R_2	If X is X_2, Then Z is Z_2
R_3	If X is X_3, Then Z is Z_3

Using the Center-of-Gravity Method, the controller de-fuzzifies the output variable to get the final result. Equation (8) shows the Center-of-Gravity method.

$$Z_i = \frac{\sum_{i=1} step\times(y_{left}+4x_{center}y_{center}+x_{right}y_{right})/3}{\sum_{i=1} step\times(y_{left}+4y_{center}+y_{right})/3} \quad (8)$$

Where, step = $(Z_{max} - Z_{min})/50$.

The designed fuzzy control iterates the algorithm until the error becomes zero ($e_{RMS} = 0$) and the resultant de-fuzzified value is added to the previous value.

3.3. PI Controller and IP Controller

Figure. 8 and 9 show the block diagrams of PI controller and IP controller, respectively [9]. PI controller generates the output in proportion to the error and to the error integral, where the error is the difference between the set value and the measured one.

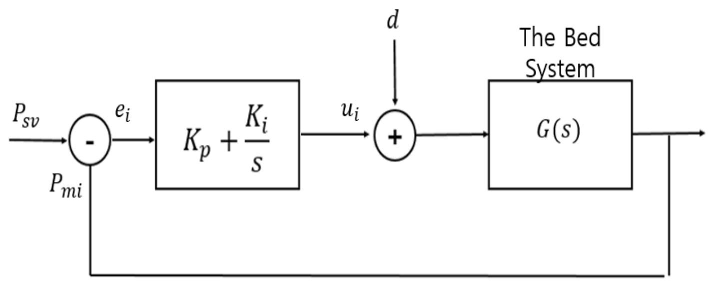


Figure 8. The PI Controller

Assume the system G(s) be the first order system, then the closed loop transfer function of PI controller can be expressed as

$$G(s) = \frac{b}{s+a} \tag{9}$$

$$G_{PI}(s) = \frac{P_{mi}}{P_{sv}} = \frac{b(k_p s + k_I)}{s^2 + (a + bk_p)s + bk_I} \tag{10}$$

Where, a,b are constants and k_P,k_I are the proportional and integral control gains, respectively. From the equation (10), the zero exist in s_z=-k_I/k_p, so the overshoot increases due to this zero. However, it is well known that PI control has overshoot. The overshoot problem in PI control can be solved using the IP control. IP controller generates the output in proportion to the error integral and to the measured output like as shown in the equation (10).

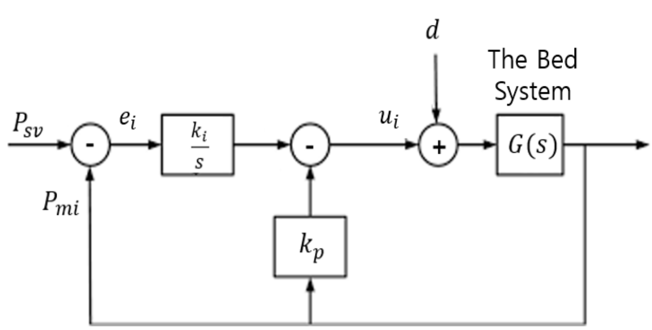


Figure 9. IP Controller

Assume the system G(s) be the first order system, the transfer function of the block diagram in Figure. 9 can be represented as

$$G_{IP}(s) = \frac{P_{mi}}{P_{sv}} = \frac{bk_I}{s^2 + (a + bk_p)s + bk_I} \tag{11}$$

From the equation (11), we can see the overshoot in PI control disappears in IP control because there is no zero.

3.4. Open-loop bang-bang control

The major cause of PU is pressure x time, which means when the pressure exceeding the critical pressure lasts over time, the ulcer begins.When the closed-loop control using body pressure sensor is failed (because of several reasons in rare cases), we change periodically pressure position, that is open-loop time control. In principle, the maintenance in body posture should take less than two hours, but the shorter the time to prevent the occurrence of the PU, so the pressure control program has been designed to repeat every T1+T2 (=10minutes.i.e.) that the unidirectional keyboard falls during T1 (=7minutes) and the flatbed keyboard is maintained during T2 (=3minutes.i.e.). This movement of the keyboard repeats periodically. Therefore, the change cycle is to set up once every 10 minutes, shorter than the 2 hours at which the change in body pressure occurred, so that there would be no change in skin tissue by the critical PU.6 The open-loop duration time control of body pressure is presented in Figure. 10.

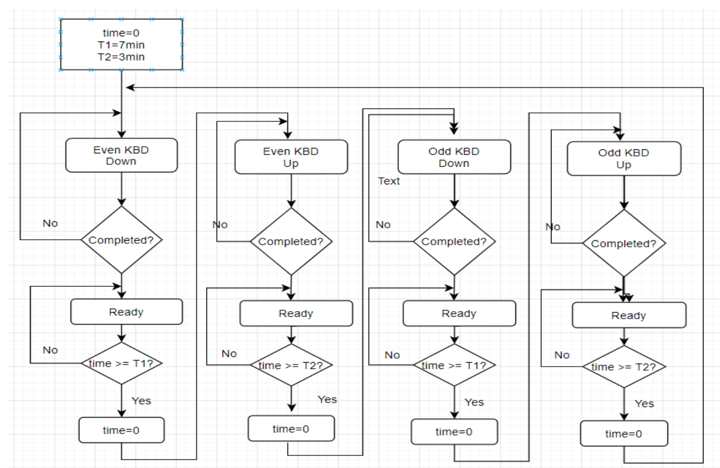


Figure 10. The periodic change of pressure (Open-loop bang-bang control)

4. Experimental Results

4.1. Fuzzy Control

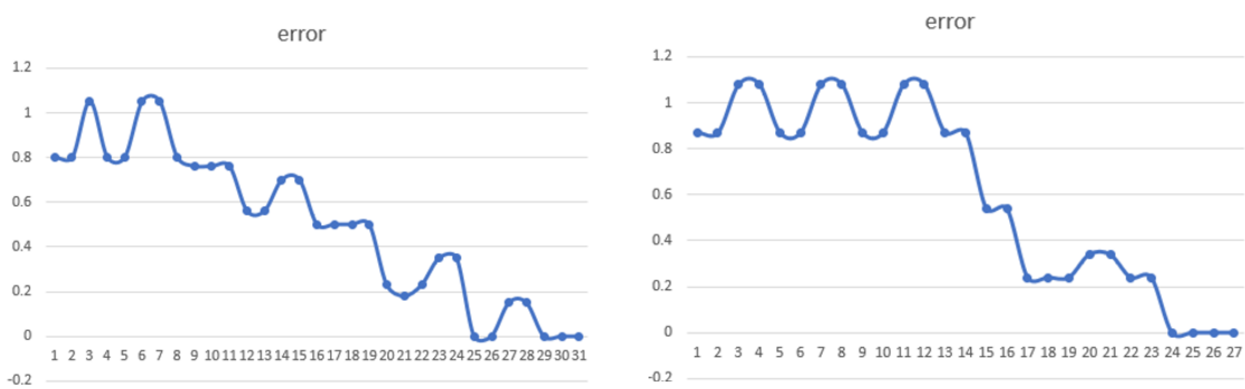
The real experiment was performed on the developed bed, where a man is in lying state. In Table 2, the key 10 and 14 exceeded the critical ulcer pressure P_{cu}(=32mmHg) and the errors occurred but the error on each key became zero after 10 iterations of the closed control loop.

Table 2. Test Result

Key number	Error before control (%)	The Maximum pressure before control(mmHg)	Error after control (%)	The Maximum pressure after control(mmHg)l	Height (mm)
1	0	0	0	0	0
2	0	0	0	0	0
3	0	23	0	21	0
4	0	0	0	0	0
5	0	23	0	24	0
6	0	29	0	29	0
7	0	0	0	0	0
8	0	15	0	28	0
9	0	28	0	29	0

10	3.125	33	0	31	-5
11	0	0	0	0	0
12	0	20	0	24	0
13	0	25	0	30	0
14	28.125	35	0	32	-31
15	0	31	0	30	-15
16	0	0	0	0	0
17	0	25	0	31	-15

Figure. 11 shows the errors in the supine posture and the side-lying one, while the iterations repeat, respectively. It presents that the closed-loop of the fuzzy controller works well. However, in a rare case, if the error does not converge to zero within the maximum predefined iteration number in the first fuzzy control stage, the open-loop up-down motion control of keyboard alternation begins to prevent ulcer, which is second stage control. Thus, there would be no room for ulcer occurrence in our approach.



(a) Supine (b)Side-Lying

Figure 11. The Error Log Samples

4.2. PI and IP Control

The control gains of PI controller and IP controller are shown like as in Table 3 and 4, respectively.

Table 3. PI gain parameters for PI control

K_P	K_I	P_{SV} [mmHg]
0.5	0	32
0.5	1	32

Table 4. IP gain parameters for PI control

K_P	K_I	P_{SV} [mmHg]
0.3	0.3	32
0.3	1.2	32

A man of 175cm and 88kg was the target of experiment. The error log plot of PI control is shown in Fig. 12 and the one of IP control in Figure. 13.

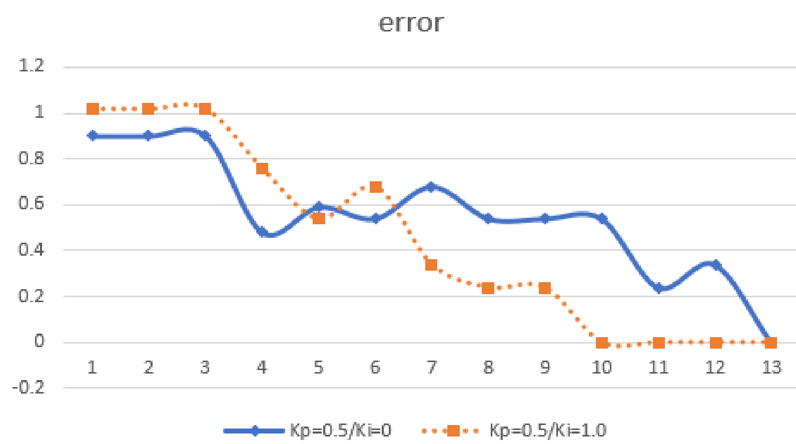


Figure 12. The error plot of PI control(supine)

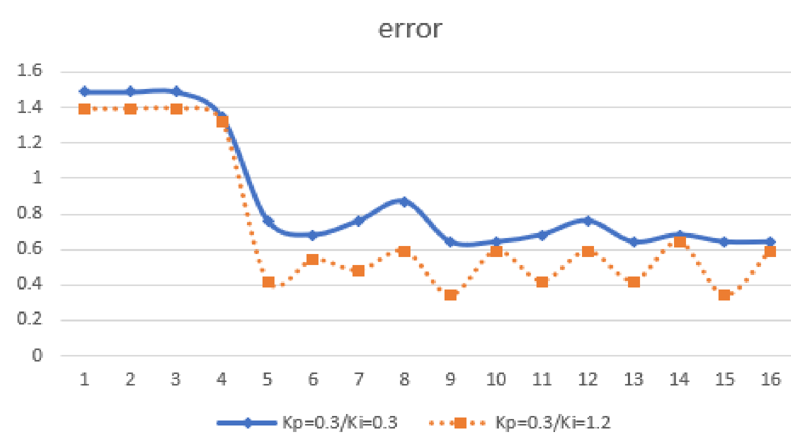


Figure 13. The error plot of IP control (Supine)

As shown in Figure. 12 and 13, we can see that the convergence of PI controller toward zero is faster than IP control. In IP control, we see there is oscillation occurred near zero.

5. Discussion

In this work, we presented two-stage controller tor preventing PU for the developed robot bed system. The first stage is the closed loop control of body pressure which adjust the body pressure to be within the critical one 32mmHg using the body pressure sensor while maintaining the comfortability of a body. Three closed loop controllers were tested: fuzzy controller, PI controller and IP controller. Fuzzy controller based on artificial intelligence showed the best performance among three methods in convergence rate. However, the robustness of convergence of fuzzy controller has not been theoretically proved until now. PI controller showed the better results than IP one in our experiments from the viewpoint of convergence rate. It is well known that PI controller has overshoot problem but it may not cause the problem in our case. Any way, we can see that the proposed controllers perform well on the developed bed system though the perfect transfer function of a human body is not well known. The set pressure for the controllers can be below the critical ulcer one but how much it can be lowered should be tested further more. The second stage of control is the open loop control without using the pressure sensor information based on alternating keys up and down periodically within a short time when the closed loop controls fail. Many air mattresses on market adopt the open loop control. It can reduce the area size of ulcer pressure but it cannot prevent PU perfectly because the residual pressure always exceeds the critical one 32mmHg. However, the residual pressure becomes zero in our bed when the key down and the duration time is set to be very shorter than the critical time of ulcer generation when the key up. Therefore, there would be no room for PU generation in our two-stage control. Meanwhile, temperature and humidity may worsen the ulcer. It is known that when temperature and humidity is high, ulcer increases. This can be lessened by lowering the set pressure of the controller below the critical one 32mmHg. However, how much it can be lowed should be further investigated. Our bed has another merit in humidity such that it has the function of air circulation because it is keyboard type. Air flows among the keys when the keys are up and down so that it dries moisture. We can increase the portion of the second stage control in humid environments. Another merit of our bed is automatic sheet exchange (ASX) mechanism using the feature of keyboard type11 The developed ASX uses a device to properly adjust tension and exchange a dirty sheet and a new sheet at the same time while the patient is in lying state without changing the posture. The developed ASX was experimentally confirmed to be properly operated and successfully installed in the bed. As a conclusion, we regard our novel bed can prevent the PU inherently and provide the function of automatic sheet exchange.

5.1. Limitation

Is it really possible to prevent PU using the newly developed robotic bed? We tried to show the performance of our bed, which is different from the conventional air mattress because it can actively control the pressure. Though theories and experiments, we showed that we can lower the pressure under critical ulcer pressure. Can the new bed replace the typical air mattress? In spite of its performance, itis currently not expected to be inexpensive because this system requires many motors and sensors. Hence, we should perform more efforts to reduce the cost. Another important question is: Is the new bed available in the clinical environment? The clinical effectiveness and usefulness should be demonstrated through appropriate clinical trials. In the near future, we have a work plan to monitor the states of the patients and to care for them remotely using the newly developed robotic bed.

6. Conclusions

In this study, we suggested a novel bed mechanism and control algorithms to prevent the PU, which suppress the body pressure to be under the critical one 32mmHg. We developed the keyboard mattress which consists of the enhanced 4 bar mechanism without inversion. We designed two-stage control. The first stage uses the closed loop control algorithms, which are fuzzy control, PI and IP control using the pressure sensor. The characteristic of three control algorithms were discussed. Despite the different properties of each controller, the body pressure is comfortably suppressed under 32mmHg which is the critical ulcer one. In this work, the fuzzy controller shows the best performance among other controls. When the closed loop control fails, the second-stage control begins which is the open loop bang-bang control. The period of open loop control is adjusted to be very short within the critical time of PU generation. Thus, there would be no room for PU in out bed system and we regard our methodology inherently prevents ulcer.

6.1 Implications

Nowadays the detecting, caring and healing techniques for PU have been evolving [2]. Though there have been many works for preventing PU, the direct control methods on pressure control are rare. In this work, we presented a novel approach to prevent PU by measuring pressure and controlling the movement of the keyboard of the electrical bed, which is very calm, clean and comfortable. We regard our current work can be a good model for other researchers, the educators and administrators.

Acknowledgement

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References

[1] M. Hahn and T. Klyscz, "Synchronous Measurement of Blood Pressure and Red Blood Cell Velocity in Capillaries of Human Skin," *J. Investigative Dermatol*, vol. 106, no. 6, pp. 1256-1259, 1996. DOI:https://doi.org/10.1111/1523-1747.ep12348955

[2] Z. Moore, D. Patton, S. L. Rhodes and T. O'Connor, "Subepidermal moisture (SEM) and bioimpedance: a literature review of a novel method for early detection of pressure-induced tissue damage (pressure ulcers)," *Int Wound J*, vol. 14, no. 2, pp. 331-337, Apr 2017. DOI: https://doi.org/10.1111/iwj.12604

[3] H. S. Cho, J. C. Ryu, G. S. Kim, M. S. Mun and I. H. Lee, “Analysis of Body Pressure Distribution Characteristics According to the Design Factors of The Air-Cell Mattress for Preventing Decubitus Ulcer,” *J. Korean Soc. Precision Eng*, vol. 24, no. 5, Jan 2004.

[4] Y. D. Lee, C. Y. Kim, C. J. Chang, M. S. Choi, J. A. Kim and J. Y. Lim, “The Control System of a Medical Robot Bed for Prevention and Healing of Pressure Ulcer,” *J. Convergence Cult. Technol*, vol. 6, no. 3, pp. 353-359, Aug 2020. DOI:https://doi.org/10.17703/JCCT.2020.6.3.353

[5] Y. D. Lee, C. Y. Kim and M. S. Choi, “Enhancement of 4 Bar Parallelogram Linkage for a MedicalBed,” *J. Convergence Cult. Technol*, vol. 6, no. 1, pp. 515-520, Feb 2020. DOI:https://doi.org/10.17703/JCCT.2020.6.1.515

[6] Y. D. Lee, J. A. Kim and H. K. Cho, “The Control System of a Robot Bed for Caring Pressure Ulcer,” *Int. J. Adv. Cult. Technol*, vol. 8, no. 3, pp. 253-258, Aug 2020. DOI:https://doi.org/10.17703/IJACT.2020.8.3.254

[7] Y. D. Lee, C. Y. Kim, C. J. Chang, M. S. Choi, J. A. Kim and J. Y. Lim, “The Control System of a Medical Robot Bed for Preventing Ulcer,” *J. Convergence Cult. Technol*, vol. 6, no. 3, pp. 353-359, Aug 2020. DOI:https://doi.org/10.17703/JCCT.2020.6.3.353

[8] L. A. Zadeh, “Fuzzy Sets,” *Information and Control*, vol. 8, pp. 338-353, 1965.

[9] F. I. Ahmed and A. M. EI-Tobshy, "P-I AND I-P controllers in a closed loop for DC motor devices," Power Conversion Conference, vol. 2, pp. 613-618, 1997. DOI:https://doi.org/10.1109/PCCON.1997.638255

[10] Y. D. Lee, M. S. Choi, C. Y. Kim, C. J. Chang, Y. Choi and G. Y. Eom, “A Study on the Automatic Sheet Exchanger for a Hospital Bed,” *J. Convergence Cult. Technol(JCCT)*, vol. 5, no. 4, pp. 361-366, Nov 2019. DOI:https://doi.org/10.17703/JCCT.2019.5.4.361