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Mathematical Model Developed Using Heat Transfer Coefficient and Clothing Permeability Factor Parameters to Prevent Pressure Ulcer

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Abstract

Pressure ulcers are wounds that occur in bedridden patients as a result of staying in the same position for a long time, due to external causes such as pressure, friction, shearing and moisture. Pressure ulcer is a serious problem all over the world when evaluated in terms of hospital capacity, nurse employment and treatment costs. Prevention studies gain importance as the cost of pressure ulcer prevention is less than the cost of treatment. In this study, we improved a mathematical model obtained in one of our previous study in order to prevent pressure ulcers or delay wound formation. In addition to the previous model, the new model calculates the effect of h_c (heat transfer coefficient) and F_{pcl} (clothing permeability factor) parameters on the risk of pressure ulcer formation through the body area value. The effects of these parameters on the formation of pressure ulcers are shown in graphics. The results obtained from the new model shown that the sensitivity in the determination of the risk of pressure ulcer formation has increased. Thus, early detection of wound formation was provided by calculating the risk of pressure ulcer formation.

Keywords: *Bedsores, Clothing Permeability Factor, Heat Transfer Coefficient, Pressure Ulcers, Risk of Pressure Ulcers.*
2010 Mathematics Subject Classification:

1. Introduction

Pressure ulcers (PU) are a regional injury that occurs on the skin or subcutaneous tissue, usually on a bony prominence, as a result of the patient's prolonged stay in the same position [1]. Pressure ulcers in patients are divided into six stages by EPUAP, NPUAP and PPPIA [2].While Stages I and II are initial wounds, in Stages V and VI, treatment requires surgical procedures. These treatment procedures bring a serious financial burden in terms of cost ([3]-[5]). Pressure injuries, also called bedsores, are one of the most common complications in many hospitals around the world [5]. Many methods have been developed to prevent this problem and continue to be developed. Surgical procedures are an extra workload and cost for hospitals. When the worldwide financial costs of pressure ulcers are examined, it is seen that the cost of prevention of this problem is less than the cost of treatment [3]. The main method used to prevent the formation of pressure ulcers is to change the position of the patient every two hours. Even for this solution, it is necessary to employ sufficient caregivers [6]. The factors affecting the formation of pressure ulcer consist of two main parts: internal factors such as age, infection,weight, malnutrition,blood pressure, skin temperature, etc., and external factors such as shear force, pressure, friction, humidity,ambient temperature, etc. [7]. There are many methods developed to decrease the effects of the external factors on the formation of the pressure ulcers such as mattresses containing air, water or gel are also used to prevent pressure ulcers [8].

The decision making process for determining the pressure ulcers is generally performed by the nurses using some risk evaluation scales such as Braden, Waterlow, Norton etc. [9]. However, a caregiver uses his/her own experience in evaluation the risk of the formation of the pressure ulcers using these risk evaluation scales [10]. On the other hand, health information technology embedded in the clinical workflow, such as clinical decision support systems (CDSS), can be used to guide professionals in making decisions and following recommended guidelines. These electronic systems are designed to create patient-specific evaluations or make recommendations by comparing the information they collected from the patient to a pertinent knowledge base.Such a system directly assists healthcare professionals in clinical decision making process. Using clinical decision support system can improve the quality of care provided and reduce the errors that may occur during the decision making process [11]. In the literature,there are many studies have been conducted for evaluating the effects of the external factors

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(pressure, temperature, humidity, wetness, etc.) on the formation of the pressure ulcers. In some of these studies, commercial mattresses (VistaMedical Ltd, X Sensor Technology Corporation, Tekscan Inc, Wellsense Inc, and the Sensor Products Inc) [12] were used while for the others the authors contributed by making their own mattresses. Chanyagorn et al. developed a system that uses Xbee (IEEE 802.15.4) modules and helps reduce the interface pressure on the patient's skin by controlling the patient's position. The system warning the nurse to change the patient position in order to prevent pressure ulcer formations while alleviating the workload [13]. Bennett et al. proposed an algorithm which detects the pressure points of a supine person for three postures (right side lying, left side lying, turning without changing the pressure zone) without any user input or assumptions [14]. Hsia et al. [15] presented a cost-effective system that uses Support Vector Machines (SVM) and Principal Component Analysis (PCA) techniques to assist healthcare professionals in detecting accurate sleep posture changes by automatically monitoring patient position over time. Khan et al. developed an application to monitor the movements of the patients who have been sitting for long periods of time, as well as weight shifting using an accelerometer [16]. Yip et al. proposed a low-cost continuous pressure monitoring system incorporating 99 capacitive pressure sensors on a $17x22\ cm^2$ mattress to determine the size, location, and time of pressure points on a patient [17]. Carvalho et al., developed a system that includes textile and polymer applications having the functions of monitoring and controlling the pressure in the body parts in contact with the support surfaces to sensitively perceive the feeling of discomfort in people with pressure ulcers and increase their life quality [18]. A mattress was designed by Liu et al using pressure-sensitive comfortable textile sensors for monitoring sleep posture. Based on high-resolution pressure distributions from the mattress, pressure image analysis is performed to monitor sleep postures [19]. A model was developed by Lee et al. using a wearable robot that warns when the pressure value ($32\ mmHg$) reaches the breaking time [20]. In [21], a new prototype matrix was designed and developed by Marenzi et al. to calculate the pressure distribution on aperson sitting in various areas such as automotive, ergonomics and clinical environments. In the studies mentioned above, it is aimed to alleviate the workload of the nurse. In addition to these, some mathematical studies on skin damage in the literature are given in [22]. Mathematical model studies have also been carried out that use external parameters such as pressure, temperature, humidity and wetness to prevent pressure ulcers. A mathematical model study was conducted by Gefen in [23] using the parameters of pressure, temperature and humidity. In [12], Demircan et al. added the wetness parameter to the model by Gefen [23] in addition to the pressure, temperature and humidity parameters. Mishu et al. [24] proposed a mathematical model for estimating the risk of pressure ulcer formation combining Waterlow risk assessment scales for bony regions of the body.

In bedridden patients, sudden wetting may occur due to urinary incontinence, defecation, serum spillage, etc. This has the effect of accelerating the formation of pressure ulcers by sensitizing the skin. For example, the PH level may increase due to bacterial growth that can cause skin infections due to frequent cleaning of the skin that is wet with urine, feces, double incontinence (combined urinary and fecal incontinence). This makes the skin susceptible to scar formation. In the literature, it is seen that wetness increases the formation of pressure ulcers in patients ([25]-[27]).

In this study, the equation for calculating the amount of sweating and calculating the amount of evaporation of perspiration in the mathematical model proposed in [12] has been updated. We added the effect of h_c (heat transfer coefficient) and F_{pcl} (clothing permeability factor) parameters to the pressure ulcer risk calculation. The paper is organized as follows. In the second part; the mathematical model developed is explained, the accuracy of the mathematical model is shown in the graphics with the values given in the third section, and the paper is concluded in the fourth section.

2. Developed Mathematical Model

In this study, the mathematical model was developed by the authors in one of their previous studies for the prevention of pressure ulcers was used [12]. This mathematical model is given in [12, Equation 16]. The model basically calculates the pressure ulcer risk using the parameters of pressure, temperature, humidity and wetness. In addition to these parameters, it also uses the parameters of body temperature, hypothalamus temperature (core temperature), amount of water lost unintentionally and regional sweating coefficient. The mathematical model developed in [12] is based on the equation in which the net sweat amount obtained by subtracting the evaporation rate of perspiration and the amount of sweat absorbed by the clothing from the perspiration rate is calculated. In this study, the mathematical model has been updated by using the equations given in [28] for the evaporation of perspiration (Ev) and maximum evaporation ($Ev_{\max}$)and then the evaporation rate of perspiration is obtained. Moreover, the effect of h_c and F_{pcl} parameters are also included in the calculation of pressure ulcer risk. The following equation was used for the evaporation of perspiration (Ev) [28].

$$Ev = \min\left(\frac{Sw * 40.6}{A_d}, Ev_{max}\right). \tag{2.1}$$

To calculate the evaporation of perspiration ($Ev\left(W/m^2\right)$), in Equation 2.1, the minimum value between the maximum evaporation of perspiration ($Ev_{\max}\left(W/m^2\right)$) and the ratio of perspiration amount ($Sw\frac{g}{\min}$) to body area $A_d\left(m^2\right)$ is taken. Here, the value 40.6 is a constant used for unit conversion ($J\min/g/s$). A_d is the body surface area calculated in [29] (DuBois formula). The equation given in [28] for $Ev_{\max}$ is as follows.

$$Ev_{\max} = 2.2 \times h_c \times F_{pcl} \times (P_s - RH \times P_a). \tag{2.2}$$

In Equation 2.2,h_c is the heat transfer coefficient, F_{pcl} is the clothing permeability factor, P_s is the saturated water vapor pressure at body temperature, and P_a is the saturated water vapor pressure at ambient temperature. RH (relative humidity) is defined as the ratio of the water vapor pressure in the air to the maximum water vapor pressure in the relevant region and takes a value between 0 and 1. When RH approaches 1, the evaporation rate of perspiration begins to slow down, and when $RH = 1$, evaporation stops completely. Equation $\dot{Ev}$ given in [12] means the ratio of the evaporation amount of sweat to the maximum evaporation amount and is as follows:

$$\dot{Ev} = \frac{Ev}{Ev_{\max}}(1 - RH). \tag{2.3}$$

When we update the equation ($\dot{E}v$) in Equation 2.3 with the equations in Equation 2.1 and Equation 2.2, we get the equation given below:

$$\dot{E}v = \frac{\min\left(\frac{Sw*40.6}{A_d}, 2.2 \times h_c \times F_{pcl} \times (P_s - RH \times P_a)\right)}{2.2 \times h_c \times F_{pcl} \times (P_s - RH \times P_a)} (1 - RH). \tag{2.4}$$

When we arrange the Equation 16 given in [12] according to Equation 2.4 to calculate pressure ulcer risk, we get the following equation:

$$t_c = \begin{cases} \dfrac{\theta_{S0} - 0.4P}{(0.5P + 0.8\theta_{s0}) \left\{ \frac{\gamma x \{W_s \Delta T_s + W_H \Delta T_H\} 2^{(T - T_0)/10} + PI}{Sw_{\max}} - \frac{\min\left(\frac{Sw*40.6}{A_d}, 2.2 \times h_c \times F_{pcl} \times (P_s - RH \times P_a)\right)}{2.2 \times h_c \times F_{pcl} \times (P_s - RH \times P_a)} (1 - RH) - Dr \right\}}, & k = 0 \\ \dfrac{\theta_{S0} - 0.4P}{(0.5P + 0.8\theta_{s0})} (1 - Dr), & k = 1 \end{cases}. \tag{2.5}$$

In Equation 2.5, P gives the applied pressure value and θ_{S0} gives the initial value of the shear strength applied to the skin. γx is the sweat rate coefficient depending on body regions. T_s is body temperature and T_H is hypothalamus temperature. W_s and W_H are equations that calculate body temperature change and hypothalamus temperature change, respectively. PI (0.63 $g/\min$) is the amount of water lost unconsciously during sweating. T and T_0 values give the temperature and initial temperature values of the relevant body region, respectively. The $Sw_{\max}$ value is the maximum sweating rate and is approximately 16.2 ($g/\min$) [12]. Dr determines the property of the substance that the body comes into contact with and takes a value between $0-1$. If Dr is 0, the clothing does not absorb sweat like a nylon outfit. Here k stands for wetness. When the k value is 0, it means no wetness, and when it is 1, it means there is wetness.

In the model developed by the authors in [12], the parameters of body temperature, hypothalamus temperature,amount of water lost unconsciously and regional sweating coefficient were effective in the calculation of pressure ulcer risk. In this study, the effects of h_c and F_{pcl} parameters were added to the mathematical model through the A_d value.

The risk calculation results of the mathematical model we obtained are tested according to varying pressure, temperature and humidity values and shown on the graphs in the next section. In addition, the effects of h_c and F_{pcl} parameters are also explained with graphics. Since the equation did not change in this study, the wetness parameter was not considered.

3. Results and Discussion

In this section, firstly, the graphical results of the newly developed mathematical model are compared with the results of the model proposed in our previous study [12]. This comparison was made according to varying body temperature, pressure and relative humidity values. Then, we examined the effects of changes in h_c and F_{pcl} parameters, which we included in the newly developed model, on pressure ulcer risk for varying pressure, body temperature and relative humidity values. In these graphs, the risk value in the formation of pressure ulcers is shown with dimensionless time. In the evaluation procedure, the time taken for pressure ulcer formation is calculated. A short time indicates a high risk of scar formation. Accordingly, when the graphs show a downward slope, the risk of pressure ulcer formation is interpreted as high.

The parameter values we used in our study are as follows. Based on the statement in the literature that limits the pressure value which causes pressure ulcer formation, approaches 30 kPa [12], thus the reference range for the pressure value is accepted as $3\ kPa - 30\ kPa$. A value of 70 kPa [12] was used for the θ_0 value, which is the maximum endurance value of the body. It is assumed that the relative humidity changes between 0% and 100%, and the body temperature varies between 35°C and 40°C. h_c value is taken as 1.136 and F_{pcl} is taken as 0.89 [12]. To calculate the saturated water vapor pressure at body temperature P_a, the room temperature was taken as 25°C, and the value of the body surface area, A_d was defined as 1.78 m^2. The initial temperature value of the body was accepted as T_s0 32°C. The initial temperature value of the hypothalamus with T_h0 was accepted as 37°C, and the Th value was accepted as 37.5°C. Using these values, risk results were calculated according to the changing pressure, temperature and humidity values in the proposed mathematical model. MATLAB © (R2021a, MathWorks ©) software was used to draw the graphics, and the results are shown below.

In Figure 3.1 and Figure 3.2, the pressure ulcer risk values obtained for the previous model [12] and the proposed one are given for the pressure values varying between 3 kPa and 10 kPa and 50% relative humidity.

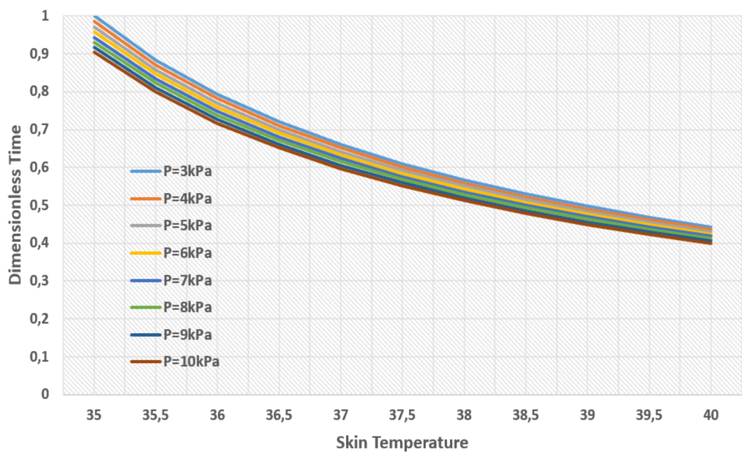

Figure 3.1: Pressure ulcer risk when the pressure value varies between 3 kPa and 10 kPa in the [12] model.

Figure 3.1 shows the risk values obtained for the model in [12] for body temperature varying between 35°C and 40°C, while the pressure value varies between 3 kPa and 10 kPa. The risk of pressure ulcer formation increases from 1 to ~ 0.45 as the pressure value increases from 3 kPa and body temperature from 35°C to 40°C. The risk value is ~ 0.9 when the body temperature is 35°C for a pressure value of 10 kPa, and ~ 0.39 when it is 40°C.

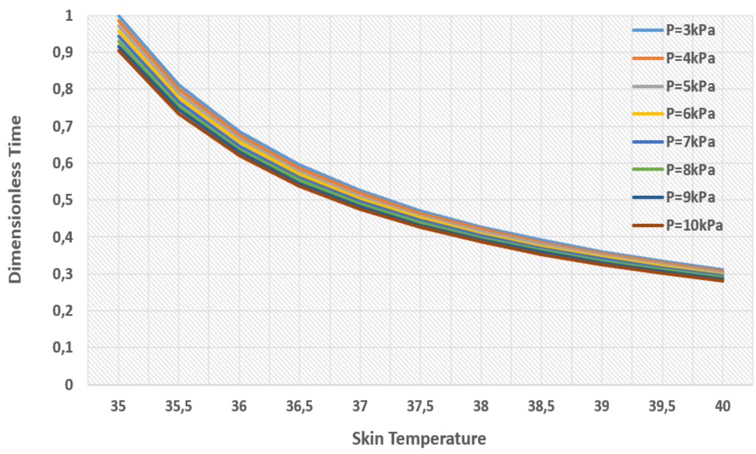

Figure 3.2: Pressure ulcer risk when the pressure value varies between 3 and 10 kPa in new model.

In Figure 3.2, the calculated pressure ulcer risk values of our newly developed model are seen for body temperature varying between 35°C and 40°C, while the pressure value varies between 3 kPa and 10 kPa. The risk of pressure ulcer formation reaches from 1 to ~ 0.31 when the pressure is 3 kPa and the body temperature increases from 35°C to 40°C. For a pressure value of 10 kPa, when the body temperature is 35°C, the risk value is ~ 0.9, and when it is 40°C, it is ~ 0.28. In the results in Figure 3.1 and Figure 3.2, it is seen that the pressure value as well as the body temperature change increase the pressure ulcer risk more rapidly. In addition, when we compare the graphs in Figure 3.1 and Figure 3.2, it is seen that the risk values of the model we developed in this study give more sensitive results than the model developed in [12].

In Figures 3.3 and 3.4, pressure ulcer risk while relative humidity is changing between 0% and 100% and the body temperature varying between 35°C and 40°C for the two compared models are given, respectively. We should note that the pressure value is taken as 30 kPa for this test.

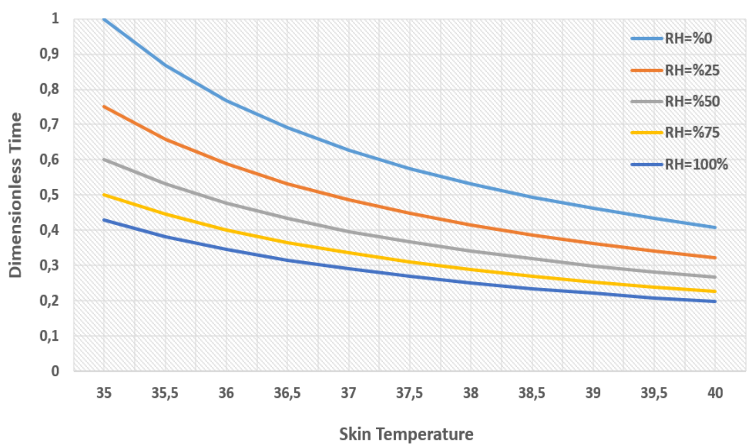

Figure 3.3: Pressure ulcer risk when the relative humidity value varies between 0%, and 100% in [12] model.

Figure 3.3 shows the risk values for the model in [12] at body temperature varying between 35°C and 40°C, while the relative humidity value varies between 0% and 100%. The risk of pressure ulcer formation increased from 1 to ~ 0.4 at 0% RH while body temperature increasing from 35°C to 40°C. And, the risk value increased from ~ 0.43 to ~ 0.2 while body temperature increasing from 35°C to 40°C for 100% RH. Increasing body temperature accelerates the formation of pressure ulcers with its effect on relative humidity.

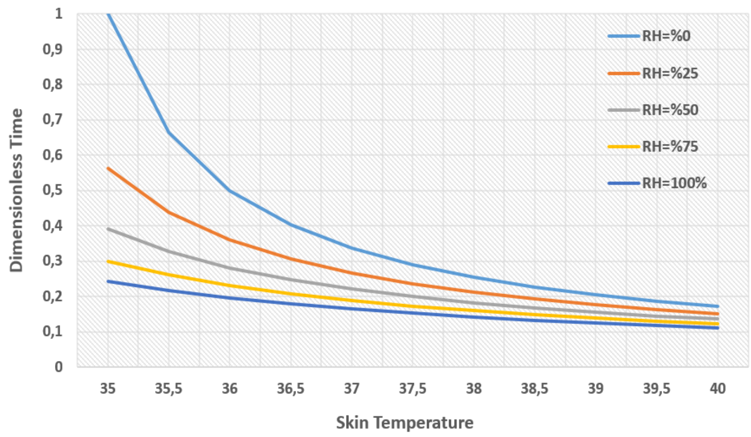

Figure 3.4: Pressure ulcer risk when the relative humidity value varies between 0%, and 100% in new model.

In Figure 3.4, the risk of pressure ulcer formation increased to ~ 0.17 at 0% RH and body temperature increased from $35°C$ to $40°C$. The risk value increased from ~ 0.24 to ~ 0.1 while body temperature increased from $35°C$ to $40°C$ for 100% relative humidity. When the two graphs are compared, it is seen that a more sensitive measurement is made with the new model.

When we compare the models in Figure 3.3 and Figure 3.4, it is seen that the increased pressure, relative humidity and body temperature increase the pressure ulcer risk in both graphs, and the results of the new model are more sensitive than the model in [12]. This situation also gives the result that pressure ulcer risk detection will be faster which is important for the prevention of pressure ulcers.

The effects of h_c and F_{pcl} parameters added to the pressure ulcer risk calculation with the new model we developed are shown in the graphs below.

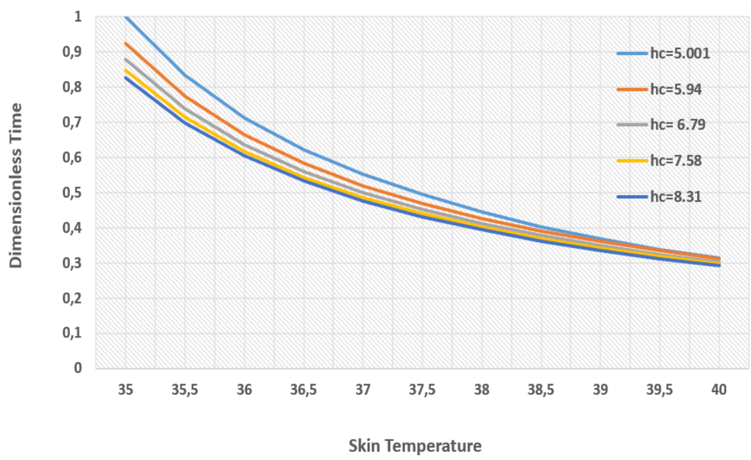

Figure 3.5: Pressure ulcer risk when the h_c value varies between 5.001 W/m^2 and 8.31 W/m^2.

Changes in air velocity in the environment and body postures affect the h_c value ([30], [31]). According to the changing air velocity ($v = 0.3m/s$, $v = 0.4m/s$, $v = 0.5m/s$, $v = 0.6m/s$, $v = 0.7m/s$) the h_c values obtained 5.001 W/m^2, 5.94 W/m^2, 6.79 W/m^2, 7.58 W/m^2, and 8.31 W/m^2 [32]. Ambient air velocity increases the h_c value. The pressure ulcer risk graph according to the h_c values obtained is given in Figure 3.5 for the body temperature varying between $35°C$ and $40°C$. When we examine the graph, while the h_c value is 5.001 and the body temperature is increasing from $35°C$ to $40°C$, the risk is from 1 to ~ 0.32. When the h_c value is 8.31, the risk value is ~ 0.29 when the body temperature is $35°C$ and it is ~ 0.81 for the $40°C$. As a result, it is seen that increasing h_c value increases the risk of pressure ulcer formation.

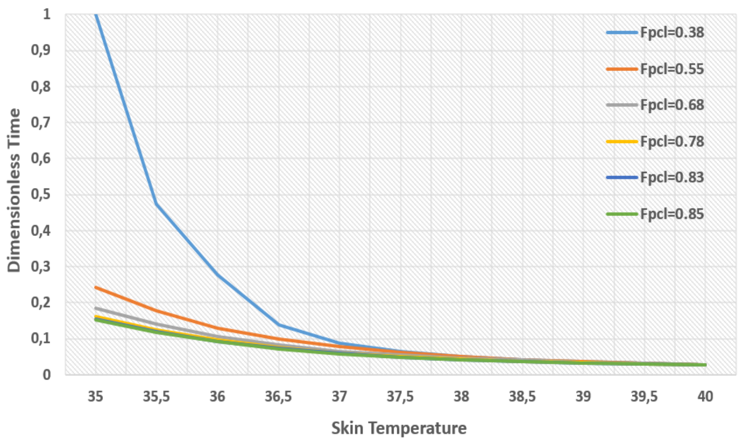

Figure 3.6: Pressure ulcer risk when the F_{pcl} value varies between 0.38 and 0.85.

F_{pcl} is calculated based on I_{cl} (Insulation of clothing) value and air velocity [33]. F_{pcl} value is 1 for naked body. We chose the I_{cl} value as 0.6 clo, which is the light clothing value for the patient. Changing air for I_{cl} value 0.6 clo ($v = 0.1m/s$, $v = 0.2m/s$, $v = 0.5m/s$, $v = 1m/s$, $v = 2m/s$, $v = 5m/s$) the F_{pcl} values according to their velocities are 0.85, 0.83, 0.78, 0.68, 0.55 and 0.38, respectively [34]. As the air velocity increases, the F_{pcl} value decreases. The pressure ulcer risk graph according to the F_{pcl} values we obtained is given in Figure 3.6 for the body temperature varying between $35°C$ and $40°C$. When we examine the graph, while the F_{pcl} value is 0.38 and the body temperature is increasing from $35°C$ to $40°C$, the risk value is from 1 to ~ 0.027. When the F_{pcl} value is 0.85, the risk value is ~ 0.15 when body temperature is $35°C$, and ~ 0.026 for the $40°C$. According to the results, it is seen that decreasing F_{pcl} value increases the risk of pressure ulcer formation.

4. Conclusions

In this study, we improved the mathematical model in [12] to be used to prevent pressure ulcers or delay wound formation. The mathematical model processes pressure, temperature, humidity, and wetness data to calculate pressure ulcer risk. While calculating the pressure ulcer risk, unlike the other study A_d, h_c and F_{pcl} parameters were also used. With these added parameters, more precise results were obtained in risk calculation. According to this;
1. The equations that calculate the evaporation rate of perspiration in the mathematical model developed in [12] have been updated. With these updated equations, the effect of h_c and F_{pcl} values are included in the pressure ulcer risk calculation with the help of the A_d value. When the new model is compared with the previous model, it was observed that the sensitivity of the risk value increased while the pressure value changed in the range of $3\ kPa - 10\ kPa$ and the body temperature changed in the range of $35°C - 40°C$. While the risk value was ~ 0.39 in the previous model, this value increased to ~ 0.28 in the new model.
2. The risk outcome for body temperatures varying between $35°C$ and $40°C$ while the relative humidity value ranged from $0\% - 100\%$ compared to the previous model was investigated. While the risk value was ~ 0.2 in the previous model, it is seen that this value increased up to ~ 0.1 in the new model.
3. The risk values were calculated for the varying values of 5.001 W/m^2, 5.94 W/m^2, 6.79 W/m^2, 7.58 W/m^2, and 8.31 W/m^2 of the h_c parameter. It is seen that the risk value increases up to ~ 0.29 at body temperatures changes between $35°C$ and $40°C$.
4. Finally, the risk values were calculated for the varying 0.85, 0.83, 0.78, 0.68, 0.55 and 0.38 values of the F_{pcl} parameter. It was observed that the risk value increased up to ~ 0.026 at body temperatures varies between $35°C$ and $40°C$.
In addition to the advantages mentioned above, the proposed mathematical model has some limitations that can be expressed as follows. Pressure ulcer formation may vary according to the patient due to internal factors originating from the patient. This subjectivity is a consideration when calculating the pressure ulcer risk. It is difficult to fully evaluate this situation using the model.
Parameters to evaluate patient-specific conditions can be added to the developed mathematical model at a later stage. Thus, with the appropriately added parameters, the model can be adapted to the specific conditions of the patients. Thanks to the developed model, the sensitivity of the patient's risk of wound formation has been increased. The main purpose here is to develop an auxiliary model for a system that supports the caregiver to make the right decision and to reduce its burden. Thus, the formation of pressure ulcers will be prevented and treatment costs will be reduced.

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Author's contributions

The author contributed to the writing of this paper. The author read and approved the final manuscript.

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