Biomechanical Changes on the Typical Sites of Pressure Ulcers in the Process of Turning Over from Supine Position: Theoretical Analysis, Simulation, and Experiment

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Abstract—Pressure ulcers are mainly caused by prolonged pressure on local tissues. The current method of preventing pressure ulcers is mainly to change the patient’s position by turning, so it is significant to study the biomechanics of the typical site of pressure ulcers. Based on anatomical theory, a three-dimensional model of the shoulder and hip was established, and the theoretical contact pressure between the body and the bed was calculated by force analysis. Then, finite element models of typical parts of pressure ulcers were established, and the maximum stresses under different boundary conditions were obtained by finite element analysis. Finally, a human body turning experiment was conducted using a pressure distribution sensor, and the pressure distribution clouds and maximum contact pressure curves under different turning angles were obtained. The results show that the extreme point of maximum stress occurs at 90°, producing a stress concentration phenomenon; the peak stresses at the shoulder and hip are more balanced in the angular threshold range of 30° to 45°, the stresses are more dispersed, and there exists an angular threshold for optimal integrated pressure, which can improve the efficiency of the use of assisted turning equipment. The relevant results help to explain the causes of pressure ulcer disease and can provide clinical references to improve the effectiveness of care.

Keywords—Turning over, Pressure ulcers, Contact pressure, Biomechanical stimulation, Rehabilitation technical aids.

BACKGROUND

Pressure ulcers, also known as decubitus ulcers, are localized injuries to the skin and subcutaneous tissue caused by pressure or a combination of pressure and shear forces. Various mechanical parameters including friction, shear stress, pressure, and microclimate are considered as potential triggers of pressure ulcers, with pressure being the main predisposing factor. Prolonged pressure on local tissues causes excessive tension within the tissues and pressure ulcers are caused when soft tissues are squeezed by bones. Pressure ulcers usually occur in areas of bony prominences, such as the scapula, sacrococcygeal area, and the back of the skull.

The risk of death in critically ill patients suffering from pressure ulcers will increase 4-fold. Prevention of ulcers is more cost-effective than treatment of ulcers, especially stage IV ulcers, and the incidence of pressure ulcers can be reduced by 50–60% with effective prevention. The prevention of pressure ulcers is focused on relieving backpressure, reducing exposure time, and improving skin health. The common method is to change the patient’s position by turning every two hours, and with the development of technology, rehabilitation robots can also be used, which requires good human–machine coupling. Seo et al. discussed the development of an intelligent bed robot system, and monitoring using an array of pressure sensors, the bed posture and movement of the patients were measured and evaluated. Some researchers have also studied the effect of nursing sup-
plies on pressure ulcer prevention through tests and controlled experiments. Santamaria et al. investigated the effectiveness of multilayer silicone foam soft dressings for pressure ulcer prophylaxis through a randomized controlled trial of multilayer silicone foam soft dressings applied to 440 trauma and critically ill patients in the emergency department and demonstrated the effectiveness of foam soft dressings for pressure ulcer prophylaxis.

However, experimental methods are time-consuming, expensive, and require a large number of experimental samples. Some scholars have attempted to solve these problems by establishing a finite element model for biomechanical analysis, building biomechanical models can provide another perspective for understanding and solving practical clinical difficulties. Skeletal and muscle models of the human locomotor system based on computed tomography (CT) data, and an in-depth discussion of how to prevent pressure ulcers. Lusting et al. used a female hip model simulated with a conventional foam mattress and a minimal tissue deformation mattress to demonstrate that local, sustained pressure concentrations can be relieved by a well-soaked and covered support surface, which can protect patients from pressure ulcers. Luo et al. developed a finite element model of the shoulder to study the effect of bone protrusion on contact stresses in the shoulder, and experimentally verified the feasibility of finite element analysis of contact stresses. However, most of the current studies on pressure ulcers from biomechanical aspects predict the contact pressure between the human body and the mattress, and few studies have been conducted on the interaction mechanisms of the internal tissues of the human body, and the studies have focused on the analysis of a certain posture, such as sitting posture and supine posture, and no studies have been conducted on the biomechanical changes in the process of turning over from supine position.

According to the human structure, the scapula, sacrum, and lower leg bones form a plane that supports the entire body weight in the supine position, and tilting affects the strain distribution, taking away the highest peak strain in the sacrum. The probability of developing pressure ulcers varies in different parts of the body, the areas prone to pressure ulcers are shown in Fig. 1, and in the same part of the body, biomechanical changes occur during the turning process. Therefore, it is significant to study the biomechanics of the typical site of pressure ulcers during turning over from the supine position, which can comprehensively reveal the mechanisms of skeletal and soft tissue interactions as well as the displacement and intrinsic stress changes of the internal structures of the human body, to better guide pressure ulcer care, such as optimal care angles and specific care positions.

In this study, a theoretical and finite element model of a typical site of pressure ulcers was developed and a turning experiment was performed. The pressure changes during human turning were depicted, the relationship between contact pressure and turning angle was obtained and the reasonable pressure distribution of the human body was discussed. The interaction mechanisms and stress changes of bones and soft tissues in pressure ulcer-prone areas during lateralization were revealed from a biomechanical perspective.

METHODS

From an anatomical perspective, pressure ulcers are prone to occur in skeletal protuberance in which the place under pressure and lack of fat protection, no muscle wrap or muscle thinness. Without the muscle between the bone and the skin to bear the buffer and decompression, the stress concentration phenomenon will occur in the skin of skeletal protuberance when the skeletal protuberance bears the vertical pressure. The following image shows the typical sites of pressure ulcers in different positions of the human body in the bed (Fig. 1), where the position of pressure ulcers on only one side is shown.

The black circles represent the location of pressure ulcers and the area of pressure ulcers that may occur. As the supine lateral position was performed with the legs flexed, the hands on the abdomen, and the soles of the feet in contact with the bed, the heels did not come into contact with the bed during lateral turning, so areas prone to pressure ulcers such as the heels were not analyzed. Because most of the bodyweight concentrates in the upper body and the pressure on one side of the body increases in turning over from the supine position, the typical and main sites of pressure ulcers are focused on the scapula and hip-sacrum in this movement.

Theoretical Force Analysis of the Main Pressure Ulcers Sites

The skeletal protuberance of the shoulder and hip is the main site of pressure ulcers in the process of turning over from the supine position. Furthermore, the vertical force related to shear force is the main factor in the occurrence of pressure ulcers. Therefore, the study on the contact pressure between the skeletal protuberance of the shoulder and hip and the horizontal bed surface can better explain the cause and prevention of pressure ulcers in a different angle of the supine position.
Three-dimensional reconstruction of the human skeleton was performed using MIMICS (Materialise's interactive medical image control system) software, and models of the scapula and hip-sacrum were obtained by threshold segmentation. Then, through theoretical analysis and calculation of bone extrusion soft tissue in the process of turning over from the supine position, it is expected to obtain the contact pressure variation between the main parts of the pressure ulcers and the horizontal bed surface. Because the right direction of turning over from the supine position is symmetric with the left direction, the rightward roll motion was analyzed only.

The extrusion force on one side of the body increases in turning over from the supine position. Theoretical force analysis of the scapula in the process of turning over from the supine position is shown in Fig. 2. When the angle of the lateral position is \( \theta \), the soft tissue at the left scapula is in contact with the bed and is subjected to the combined action of \( G_{sb} \), \( G_{lb} \), and \( G_B \), the uniformly distributed load is

\[
F_{N1} = G_{sb} + (G_B + G_{lb}) \sin^2 \theta
\]

where the scapular and the spine initial force are \( G_{sb} \), \( G_{lb} \), and \( G_B \). The angle between the scapular plane and the chest plane is 30°. Among them, the force at the sacrum is \( F_{N3} \). The force at the hip is \( F_{N4} \). Based on medical software measurement, the angle between the hip plane and the chest plane is about 45°.

When the scapula does not touch the bed, \( F_{N3} = 0 \).

According to the weight parameters of the human body, the following assumptions are made: \( G_B \) is 150N, \( G_{sb} \) and \( G_{lb} \) are 30N, \( G_H \) is 400N. According to human anatomy, the ratio of shoulder blade width at the upper arm to that at the back is about 2:3. The ratio \( \lambda \) of the initial weight of one hip to the total weight of the hip \( G_H \) is 0.5.

Considering the contact pressure and contact area between the scapula and hip-sacrum and the bed surface are varied, the stress should be used as the standard to evaluate the best lateral position. Information on the length of the contact area between the scapula and the hip-sacrum and the bed surface is measured by MIMICS. CAD (Computer-Aided Design) is then used to calculate the area of the contact area and estimate the area in different states based on the shape of the bone. Finally, the pressure changes of the scapula and hip-sacrum were calculated using the pressure equation

\[
P = F/S.
\]

**Biomechanical Modeling of the Main Pressure Ulcers Sites**

Based on the CT scan slices of a healthy man, the three-dimensional reconstruction of the bone was carried out. Then, the 3D skeleton was imported into Geomagic Studio software and optimized by repairing holes, removing features, removing pegs, simplifying polygons, and surfacing. Finally, the optimized bone structure was used to perform theoretical force analysis and calculation of bone extrusion soft tissue in the process of turning over from the supine position, to evaluate the best lateral position.
was imported to the ABAQUS for biomechanical modeling.12,15

The scapula, hip-sacrum, and soft tissues geometry are irregular, the model is complex, and the irregular shape increases the complexity of the simulation algorithm. Considering that the grid quality has an important influence on the calculation results, the higher the number of grids, the higher the calculation accuracy, but at the same time increases the calculation scale, so for the model that needs to calculate stress, increases its grid density. A three-dimensional tetrahedral mesh (C3D10M) was used to mesh the model separately, and the mesh was gradually refined from coarse to fine mesh, and after a mesh convergence study, an element size of 0.5–4 mm was accepted. Fixed boundary conditions were then imposed on the soft tissues, and the scapula and hip-sacrum were constrained by contact with the soft tissues. Finite element model parameters of the scapula, hip-sacrum, and soft tissues are shown in Table 1, and the finite element model is shown in Fig. 4.

The bone is divided into the cortical bone, cancellous bone, articular cartilage, etc., and the material properties of different parts of the bone vary. At present, most studies have simplified the bone into the cortical bone and cancellous bone and regarded them as homogeneous and isotropic linear elastomers. To simplify the study, the cortical bone and cancellous bone were regarded as the same material properties.12,16 The Elasticity of the scapula is 9 GPa, Poisson’s ratio is 0.3.1 The Elasticity of the Pelvis is 43.53 GPa and the Poisson’s ratio is 0.2.22

Pressure is generated when bones crush soft tissue and stress concentrations lead to pressure ulcers. Although soft tissue includes muscle, skin, and so on, to improve the efficiency of the simulation, the soft tissue is viewed as a whole and its Elasticity is 200 kPa and the Poisson’s ratio is 0.459.32

Different boundary conditions will be applied to the scapula and hip-sacrum in different states based on the theoretical force analysis of Figs. 2 and 3. The boundary conditions of five angles of 0°, 30°, 45°, 60° and 90° were set.

The details of the model of the scapula and hip-sacrum are used to illustrate the principal constraint setting better, as shown in Fig. 5.

In Fig. 5, θ is the angle between the force line and the plane of the shoulder blade, \( F \) is the vector force applied to the bone, and represents the direction of the force from the inside out. The force on the left side is always straight down and the angle between the scapula and the horizontal plane changes. The force on the right side always points to the horizontal plane from the inside of the hip. Based on the above analysis, principal constraint settings are shown that include boundary conditions and loads, as shown in Table 2. For the model details in Fig. 5, constraints are set to try to keep up with reality.

In this study, a three-dimensional model of the bones and soft tissues of the pressure ulcer-prone parts of the trunk was established regarding previous modeling methods.12,16 The optimized model was then imported into ABAQUS, and material properties and elastic moduli were set for the bones and soft tissues regarding previous experience.1,12,16,22,28 Different boundary conditions and loads were applied to the bones in different states to ensure the realism and accuracy of the finite element model through analysis of the forces on the bones and soft tissues at the shoulder and hip, analysis of the human active cartwheel process, and study of the mechanical transfer under standard cartwheel movements.

Contact Pressure Measurement Experiment in the Process of Turning Over

To explain the laws of motion, and to verify the correctness of the theoretical analysis and biomechanical modeling, the contact pressure between the shoulder blade and hip and the bed surface in the

![Diagram](a) Theoretical force analysis of the scapula in the process of turning over from supine position.
process of turning over need to be measured experimentally. The measurement subject is a healthy volunteer, male, 24 years old, 175 cm in height, 70kg in weight, with no adverse health risks, meeting the requirements of the experiment. Before the experiment, the subject had filled in the informed consent form and completed the relevant review.

The pressure distribution test system selected was a membrane pressure sensor made by TEKSCAN, USA. Pressure distribution test sensor lattice density \(0.3 \text{ point/cm}^2\), range \(0.15 \text{ kg/cm}^2\), high sensitivity, mostly used for long-term bedridden patients with pressure ulcers monitoring. The sensor contains a grid consisting of a semiconductor substrate that changes the resistance value of the internal components after a load pressure, and the most basic sensors are made up of these interleaved matrices. A quick electronic scan allows measurement of resistance data for each sensing element, and a simple calibration function allows the magnitude, time, and position of the force and pressure on the sensor to be obtained.

The pressure distribution test sensor can complete the real-time acquisition, display, and storage of multi-channel sensor information, and can realize the calculation and analysis functions such as the contact image description, the pressure map, contact area, and pressure center trajectory of various parts of the human body.

Contact pressure measurement experiment in the process of turning over will be performed as shown in Fig. 6.

Firstly, the subject lies flat on the pressure transducer with the scapula in contact with the transducer, adjusts the posture so that the arms are flat on the sides of the body, the legs are naturally straight, then the legs are flexed and the hands are naturally placed on the abdomen. Five subjects performed natural turning movements in an independent supine position at a normal turning rate, and after each lateral turn was completed, the position was readjusted and the lateral turn was repeated 15 times to collect data on the pressure changes in the human scapula. The subject lies flat on the pressure transducer with the hips in contact with the transducer. The above steps are repeated and pressure change data are collected on the human hip.

RESULTS

Theoretical Force Analysis Results

Theoretical contact pressures on the scapula and hip-sacrum during lateral rotation were obtained by analyzing the forces on the scapula and hip-sacrum using data on the actual physical parameters of the subject and by calculating the contact areas of the shoulder and hip joints with the bed at different lateral rotation angles, as shown in Fig. 7.

![Figure 3. Theoretical force analysis of the hip-sacrum in the process of turning over from supine position.](image)

**TABLE 1.** Finite element model parameters of scapula, hip-sacrum, and soft tissues.

| The typical sites         | Number of cells | Number of nodes | Minimum cell length /mm |
|---------------------------|-----------------|-----------------|-------------------------|
| Scapula                   | 81483           | 126979          | 2                       |
| Scapular-soft tissue      | 85793           | 127998          | 0.5                     |
| Hip-sacrum                | 206319          | 307689          | 2                       |
| Hip-sacrum-soft tissue    | 105429          | 160688          | 0.5                     |
In Fig. 7, the pressure of the scapula fell slightly within the range 0° to 35°, rose a small within the range 35° to 78° and then rose significantly within the range 78° to 90°. And the pressure of hip-sacrum fell largely within the range 0° to 43° and rose dramatically within the range 43° to 90°. And the lowest pressure value of the scapula and the hip-sacrum occurred in the 35° and 43° respectively. The d1 is about 5.4e3 Pa and d2 is about 5.68e4 Pa.

| Angle | Constraint | Scapula | Hip-sacrum |
|-------|------------|---------|------------|
| 0°    | Boundary Conditions | Tie with soft tissue, ③④ | Tie with soft tissue, ⑧ |
| Load  | φ=60°, ⑤ |  | F=FCos45°, |
| 30°   | Boundary Conditions | Tie with soft tissue, ③④⑦ | Tie with soft tissue, ⑧⑨ |
| Load  | φ=90°, ⑤ |  | F=FCos75°, |
| 45°   | Boundary Conditions | Tie with soft tissue, ②③④⑦ | Tie with soft tissue, ⑧⑨⑩ |
| Load  | φ=105°, ⑤ |  | F=FCos90°, |
| 60°   | Boundary Conditions | Tie with soft tissue, ②③④⑦① | Tie with soft tissue, ⑧ |
| Load  | φ=120°, ⑤ |  | F=FCos105°, |
| 90°   | Boundary Conditions | Tie with soft tissue, ②③④⑦① | Tie with soft tissue, ⑧ |
| Load  | φ=150°, ⑤ |  | F=FCos135°, |

In Fig. 4, the finite element models of scapula, hip-sacrum, and soft tissues are shown.

In Fig. 5, the details of the model of the scapula and hip-sacrum are illustrated.
Experiment Results

Comparing the results of each group of experiments, the result of each experiment can show the variation of the pressure in real-time rather than the average of many results, so an experiment is selected for the analysis of the results. The experimental data with significantly different pressure distribution and abnormal variation of pressure trajectory were excluded, and a randomly selected group of supine lateral rotation data was analyzed to obtain the pressure distribution of the scapula and hip, as shown in Fig. 8.

The horizontal and vertical lines are used to establish absolute coordinates and the position of the shoulder blades can be got. The geometric center of the shoulder blades is gradually moving to the left side and the maximum pressure area is gradually moving up to the left. And the geometric center of the hip is gradually moving down to the left side and the same as the maximum pressure area.

In figure (a), the areas of the shoulder and hip that are susceptible to pressure during lateral rotation are indicated. In figure (b), areas (1) and (2) are pressure areas on both scapulae, with the greatest pressure at the lower scapular angle in the supine position. The area of maximum pressure gradually moves upwards from the inferior scapular angle as the lateral rotation progresses and at a lateral rotation angle of 30°, area (3) in figure (c) is the point of maximum pressure, at which point the left side of the body gradually moves away from the pressure sensor and the center of gravity shifts to the right side of the body. Figure (d) shows that the contact area between the body and the sensor shifts further to the right side of the body, where pressure is generated in the area (5), indicating that the lumbar region is sharing part of the body pressure at this moment. At a lateral roll angle of 90°, the maximum pressure point moves to the shoulder crest area, the position of area (6) in figure (e), where the pressure on the lumbar region decreases.

The area of maximum pressure on the hip in the supine position is concentrated on the sacrum, where region (7) is located in figure (f). Figure (g) shows that the area of maximum pressure shifts from the sacral region to the hip region during lateral rotation, with the region (8) moving to the right side of the body relative to the region (7). The pressure distribution gradually shifts to the area of contact that is greatest over most of the hip bone. Figure (h) shows that the area of maximum pressure gradually shifts from the region of the hip bone to the lower part of the hip bone and the greater trochanter, with the region (9) continuing to move towards the lower right side of the body relative to the region (8), with the pressure distribution gradually concentrated within the region (9).

Figure (i) shows that the greatest area of pressure is concentrated in the area (10) and that the contact area decreases. The pressure distribution shows a concentration to the dispersion to concentration as the angle increases when turning over from the supine position.

This figure (j) shows that the pressure of the region scapularis gradually rose within the range 0° to 25°, relatively stable within the range 25° to 40° and rose significantly within the range 40° to 84°. The pressure of the hip-sacrum gradually fell in the 0° to 40° and increased significantly in the 40° to 90°. There were two fluctuations as the roll angle approached 75°, which could have been caused by sudden changes in roll speed or ground vibration, but the fluctuations did not affect the accuracy of the results. And the lowest pressure value of the scapula and the hip-sacrum occurred in the 30° and 40° respectively. The largest pressure change curves of the shoulder blade and hip. $d_1$ is about 8e3 Pa and $d_2$ is about 5.9e4 Pa. This is consistent with the results of the previous theoretical force analysis and verifies the correctness of the theoretical analysis.

Finite Element Analysis Results

The stress variation obtained from the simulation analysis, shown in Fig. 9b, is compared with the actual contact pressure cloud from the pressure distribution measurement experiment (shown in Fig. 8i) and it is found that the contact pressure distribution measured by the two methods is approximately the same. Comparing the simulated maximum stress curve (Fig. 9c) with the actual contact maximum pressure curve (Fig. 8j), the curves follow approximately the same trend, and the difference between the minimum pressure and the starting pressure (d1,d2) is approximately the same as the difference between the minimum stress and the starting pressure (d1,d2), with both the minimum stress and the minimum pressure at the shoulder and hip produced within a lateral flip angle of 30° to 45°. Although there are slight differences in the numerical values of the maximum stresses and the actual maximum compressive forces at the shoulders and hips calculated by the finite element simulation, the minimum stresses, and minimum compressive forces at the shoulders and hips are generated at essentially the same moments and the curves follow essentially the same trend. The results of the finite element model simulation are consistent with the experimental results, and the finite element model of the trunk pressure ulcer-prone area is valid and can be used for the simulation study of the pressure ulcer-prone location during supine lateral turning.

Based on biomechanical modeling of the main pressure ulcers sites, the finite element simulation of
the shoulder and hip is executed, and the stress changes were obtained as shown in Fig. 9.

In the stress diagram of the scapula and nearby soft tissues, the acromion and inferior angle of the scapula, the medial edge and part of the scapula are in contact with nearby soft tissues; in the stress diagram of the hip-sacrum and nearby soft tissues, part of the hip and sacrum are in contact with nearby soft tissues, as shown in Figure (a), the region I at the inferior angle of the scapula; region II at the acromion; region III at the sacrum; and region IV at the hip. In figure (b), the area of stress on the scapula in the supine position occurs mainly in the zone I; then, as the angle of body lateral position increases, most of the area of the scapula comes into contact with the nearby soft tissues and the area of stress change is gradually concentrated in zone II. During the stress change, the area of stress concentration achieved a shift from zone I to zone II. At a lateral rotation angle of approximately 30°, the contact area between the scapula and the nearby soft tissues is relatively large and the stresses are more evenly distributed over the soft tissues. Finally, when the lateral position is 90°, the stress changes are mainly concentrated in zone II. In the stress map of the hip-sacrum and adjacent soft tissues, the sacrum is in contact with the adjacent soft tissues in the supine position, while the major stresses gradually shift from zone III to zone IV as the body angle increases in the lateral position. The area of contact between the hip bone and the bed is greatest in the lateral position of 45°, where the stresses are most dispersed, and finally, when the lat-

FIGURE 6. The measurement of the contact pressure distribution.

FIGURE 7. The theoretical contact pressure of the scapula and hip-sacrum and the bed at a different angle.
eral position is 90°, the stress changes are mainly concentrated in zone IV.

Figure (c) shows that the stress of the scapula decreased slightly within the range 0° to 30° and then rose significantly within the range 30° to 90°. Moreover, the stress of the hip-sacrum decreased in the 0° to 45° and increased in the 45° to 90°. And the lowest pressure value of the scapula and the hip-sacrum occurred about the 30° and 45° respectively. The stress difference d1 in the soft tissues near the scapula is approximately 6.8e3 Pa, while the stress difference d2 in the soft tissues near the hip-sacrum is approximately 5.98e4 Pa.

**DISCUSSION**

Many factors affect the production of pressure ulcers, and pressure is the main factor that leads to pressure ulcers. Unreasonable pressure distribution in the human body is particularly likely to cause pressure ulcers, especially in areas where bones are more prominent and skin wrapping is weaker.

According to the anatomical structure of the human body, the scapula and hip-sacrum are the most prominent bones and have a large area of action on the soft tissues of the body, and most of the bodyweight is concentrated in the upper body, so it can be considered that they are the typical and main sites for the occurrence of pressure ulcers during turning in the supine position.
To estimate the biomechanical changes on the typical sites of pressure ulcers in the process of turning over, firstly, for the biomechanical study of turning over from the supine position, the pressure distribution of the bones around the main pressure ulcer areas of the trunk was analyzed and the theoretical contact pressure between the bones and the bed surface was calculated from data on the actual physical parameters of the subjects. Then, based on the biomechanical model, the maximum stress changes of these bones under different constraints were simulated. Finally, a turning-over experiment was performed to obtain the actual contact pressure between the typical site of the pressure ulcers and the bed. Theoretical calculations and simulations cannot simulate the real situation, and the experiment is also affected by many factors. However, integrating the results of theoretical analysis, experiments, and simulations, the trends and the numerical ratios of calculations, simulations, and experiments are consistent, and the study proves the pressure changes of pressure ulcers in typical parts of the trunk during turning over.17

Theoretical force analysis, finite element analysis, and experimental studies have shown that the pressure distribution in the human body varies with the angle of lateral rotation in the supine position, with the maximum pressure often occurring at the bony prominence, and that the pressure distribution varies with different lateral rotation angles. The extreme point of peak stress occurs at 90°, creating a stress concentration phenomenon, and the 90° lateral position is more prone to pressure ulcers than the 30° lateral position, which is consistent with the results of some clinical studies.7,23 The pressure distribution cloud shows that when the lateral turning angle is small or large, the contact area between the bony prominence of the human body and the bed surface is small and the stress is more concentrated, which leads to excessive local stress and increases the chance of pressure ulcers; within the angle threshold of 30° to 45°, the flat parts of the shoulders and hips are in contact with the bed surface and the pressure distribution is more dispersed.

This analysis shows that the pressure conditions in the range of 30° to 45° for the turn over angle are better than 90°. Analysis of the two graphs in Figs. 8j and 9c shows that the moment of minimum pressure generation between the shoulder and hip and the bed surface during lateral turning is between 30° and 45°. Within this angular threshold, there exists a form of contact that allows for an optimal pressure on multiple pressure ulcer prone areas, and this threshold relieves the local tissue contact pressure and provides pressure ulcer prevention. The physiological structure of the shoulder and hip allows for a situation where the outer contour of the skeleton is enveloped by soft tissue connections. With a lateral turning angle of 30° to 45° the contact area between the soft tissue and the bed is larger, and the concentrated pressure caused by the bony prominence on the nearby soft tissue is relatively small, which can effectively reduce the chance of pressure ulcers. Some researchers have shown that different angles have different effects on pressure ulcer prevention, with 90° lateral recumbency producing higher pressure than 30° lateral recumbency,7 and 30° lateral recumbency having less effect on patients’ vital signs and being effective in preventing pressure ulcers.
It can also be seen from the contact pressure cloud that the pressure points on the body in the lateral position at an angle of 30° to 45° can effectively avoid the bony prominence and can better prevent pressure ulcers without increasing the patient’s pain.

The biomechanical changes on the typical sites of pressure ulcers in the process of turning over from supine position are revealed based on theoretical analysis, simulation, and experiment. Among them, the complex skeletal movement was simplified into a staged mechanical model under the characteristic state to describe the contact between the typical sites of pressure ulcers and the bed surface during the whole turn over process, and the relationship between the contact pressure and angle is obtained. The results of calculation, simulation, and experiment show the following rules: with the increase of the angle of turning over, the pressure on the shoulder increased gradually and the pressure on the hip decreased first and then increased.

There is a phenomenon that the two lowest values appear during the turning process and the maximum value appears at the 90° position, which indicates that turning relieves the high contact pressure between the body and the bed surface. At the same time, the maximum pressure value appears at the 90° position, which indicates that the body should not be held for a long time in the position of turning at a large angle.

The maximum stress on the scapula and hip-sacrum showed the same trend as the contact pressure on the scapula and hip. There is an angular threshold within which the contact pressure between the body and the bed is minimal in these results, and this threshold can provide guidance on the angle of supine lateral rotation in clinical care, and the relevant findings can be applied to pressure ulcer care. In addition, the change in body center of gravity can be known from the contact pressure cloud, which can guide the selection of supine cartwheel assist positions and the design of cartwheel assist devices, such as the design of rigid-flexible coupled exoskeletal cartwheel assist robots that are in contact with the shoulders and hips and conform to the laws of human movement, and provide a design principle for controlling body center of gravity and assist forces.

There are some differences in both theoretical and simulation results compared with experimental results, because the gravitational forces and percentages of each part are estimated in the theoretical calculations and the boundary conditions set in the finite element simulations are too ideal. In the next study, more experiments will be conducted on more volunteers to analyze the collected data based on the existing model, to further study the biomechanical properties of the human skeleton during the turning process, and to try to simulate the skeletal stresses in real situations to build a more accurate model.

Given the paucity of studies on typical sites of pressure ulcers, but the particular importance of pressure ulcer care, this study discusses the pressure distribution at pressure ulcer-prone sites such as the shoulder and hip from a biomechanical perspective with different lateral rotation angles, and explores the supine lateral rotation angle with the lowest combined pressure distribution to reduce the maximum pressure at this site and reduce the probability of pressure ulcers. Based on this research, a more comprehensive study of other pressure sore prone areas such as the heel and ankle will be conducted later to improve the biomechanical analysis of typical human pressure sore areas and then, on the basis of this research, a lateral flip-assisted exoskeleton robot will be designed that facilitates pressure sore prevention and conforms to the laws of human movement.

There may be an optimal angle for pressure ulcers care based on the minimum contact pressure of the typical sites. Pressure-reducing devices (e.g., assisted turning robots) designed based on this threshold have better pressure-reducing effects, and clinical care guided by this threshold can effectively reduce the occurrence and recurrence of pressure ulcers. And the related results can also help to provide a reference for clinical nursing.

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