Bioengineering Research

Stress Analysis of a Nature-Inspired Skin Adhesive Patch as a Wound Closure Technique

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Abstract
Skin is the outermost layer of human body that protects it from various threats. Although the human skin acts as a protective layer, when the skin is injured it can be an open inlet for bacterial and virus attacks. Staples and sutures are used to close the skin wounds but they cause some problems such as skin irritation. Utilizing adhesive patches can be considered as an appropriate alternative to the sutures and staples. In this paper, two natural mechanisms found in the gecko toe pad and housefly feet were employed in order to improve the skin adhesive patch performance. Finite element simulations were conducted in order to study the effects of different geometrical parameters of the skin adhesive patch and achieve better performance of the patch. The proposed configuration of the skin adhesive patch can completely close the wound opening and provide effective air circulation to aid cell and tissue regeneration. Therefore, it can provide better biocompatibility with the human skin in contrast with the traditional skin adhesive patches with minimal patient inconvenience.

Keywords: Skin, Wound opening, Staples and stitches, Skin adhesive patch, Irritation

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1. Introduction

The human skin is the outermost physical layer of body that can prevent from entrance of pathogens, viruses and microorganisms [1-3]. It is important to close the wound in the shortest possible time in order to prevent pathogen entrance and to accelerate the wound healing process [4]. Every year over 26 to 90 million wounds merely in the United States need closure [5]. There are several traditional techniques for closing wounds such as staples and suture. However, these methods require skin piercing and are typically painful in the course of implementation and removing [6]. An appropriate wound closure technique should be easily applicable, quick, painless and cost-effective [7]. There are a number of issues in the traditional wound closure methods such as wound infection, excessive scarring and keloid formation. In some cases wound reopening have been also observed [8]. The skin suture can lead to irritation-based reactions of the skin and delayed healing.

Staples can be used as another technique of wound closure. The staples can increase the patient dissatisfaction in the course of implementation as it does induce new holes and can easily cause wound infections. Moreover, this method of wound closure may lead to inappropriate dermis connection in the thin and sensitive skins [9].

Adhesive patch can be considered as an appropriate alternative to the sutures and staples. The common adhesive type used in wound patches is the pressure sensitive adhesives (PSA). Webster [10] focused on processing and tailoring of the properties of medical grade PSAs since 1985. Zibigniew et al. [11] designed and fabricated an advanced biodegradable pressure-sensitive double-coated tape adhesive containing starch carrier and partially degradable water-soluble modified adhesive. The results showed appropriate tack and peel adhesion of the fabricated biodegradable self-adhesive tapes with high shear strength.

Pillai et al. [12] proposed a novel adhesive structure using the polyethylene-oxide copolymers and dendrimers for delivery of genes and macromolecules. Their proposed design can be exploited for developing a new drug-delivery system in the future. Yongli shi et al. [13] proposed transdermal drug delivery systems (TDDS) and could achieve significant success in medical applications, however, it suffered from adhesion failure and skin reaction due to the occlusive properties of hydrophobic PSAs. The results indicated that the HPSA/c-PVA composite fibrous films could provide suitable adhesive properties in TDDS, excellent capacity for drug loading and release, aesthetical appearance and high safety for use on the human skin. Even if the irritations induced by PSA adhesive patches can be avoided, the skin cells may be easily damaged due to the high adhesion of PSAs in the course of patch separation from the skin and consequently giving rise to pain, inflammation and delay in healing process. In addition, the moisture trapped underneath the skin adhesive patch can lead to skin maceration, a certain type of skin irritation seen in elderly people. This occurs due to thinning of epidermis and sensitivity of the skin in elderly patients which can increase the possibility of skin rupture. Zulkowski et al. [15] explored the superficial skin issues related to the moisture-associated skin damages and the medical adhesive-related skin injuries by providing similarities, differences, prevention methods and treatments. They reported that the entrapped moisture under the adhesive dressing can cause severe skin problems.

Stauffer et al. [16] investigated a microstructure electrodes inspired by the grasshopper feet for clinical ECG and EEG recording. They concluded that compared to gel electrodes, the soft bio-potential electrodes are nearly imperceptible to the wearer and cause no skin irritations even after hours of application.

Acrylate-based adhesive patches have been widely used as adhesive tapes due to their strong adhesive properties. With increasing demands of long-term use of adhesive patches, a method of fabricating less skin-irritating and biocompatible patches is potentially of great interest. Kwak et al. [17] presented a new type of medical skin patch in the form of mushroom-like wide-tip micro pillars. It was found that the normal adhesion on the skin surface was primarily determined by the aspect ratio of micro pillars, while the effects of tip thickness and width were observed to be negligible.

Unfortunately, some factors such as high manufacturing cost and low long-term performance have limited wider applications of adhesive tapes as replacement of sutures. Hwang et al. [19] presented a new manufacturing technique based on automated CNC machining and replica molding. This method enabled simple and scalable fabrication of bio-inspired dry adhesives. They suggested a manufacturing process that can facilitate the widespread use and commercialization of biomimetic smart dry adhesives. In other words, the next generation healthcare bio-inspired wound patches should have appropriate mechanical properties and the consistency to the skin interface. Jin et al. [20] provided a review on the main concepts and approaches related to the recent advances in the context of skin-based wearable devices.

The main function of skin is to provide a cover that can prevent the noxious and infectious agents from entering the human body while preserving underlying structures from trauma and preventing the loss of valuable body fluid. However, this can be disrupted by the skin wounds [21]. Therefore, an ideal skin patch should be biocompatible and impermeable to pathogen, able to prevent dehydration and provide a rapid and sustained adhesion to skin. These patches should have a structure to allow cell migration and aid to proliferation of new tissue and also be flexible. So it can conform to irregular skin surfaces [22]. The natural mechanisms can be utilized in order to achieve appropriate solutions for the new generation of skin adhesive patches. Although several researches have been carried out on the bio-inspired skin adhesive patches, limited works have been dedicated to stress analysis of such adhesive wound dressing and most of them have focused on biological aspects. In this paper, two bio-inspired mechanisms have been used for designing the proposed adhesive wound dressing. The used mechanisms were inspired from gecko's toe pad and housefly feet. It has been revealed that the hierarchical setae in gecko's toe pad can provide the ability of reversible adhesion [23]. Moreover, the walking mechanism of house fly (Musca domestica) was used to provide a suitable relationship between the body weight and the supporting contact configuration [24]. The effect of geometrical parameters was investigated on the performance of the proposed skin adhesive patch using finite element modeling.

2. Materials and Methods

The human skin is a dynamic and rough surface with numerous voids and hairs that is extensively under stretching, compression and bending during daily activities [11, 25]. The roughness of the body skin can significantly affect the adhesion formation between the skin and the adhesive wound dressing. The attractive forces like Van der Waals can take place when the distance between the two object surfaces is reduced to the atomic distance and thus a large area of contact can be achieved between the two surfaces. For this, at least one of the two contact surfaces needs to be very soft in terms of elasticity.

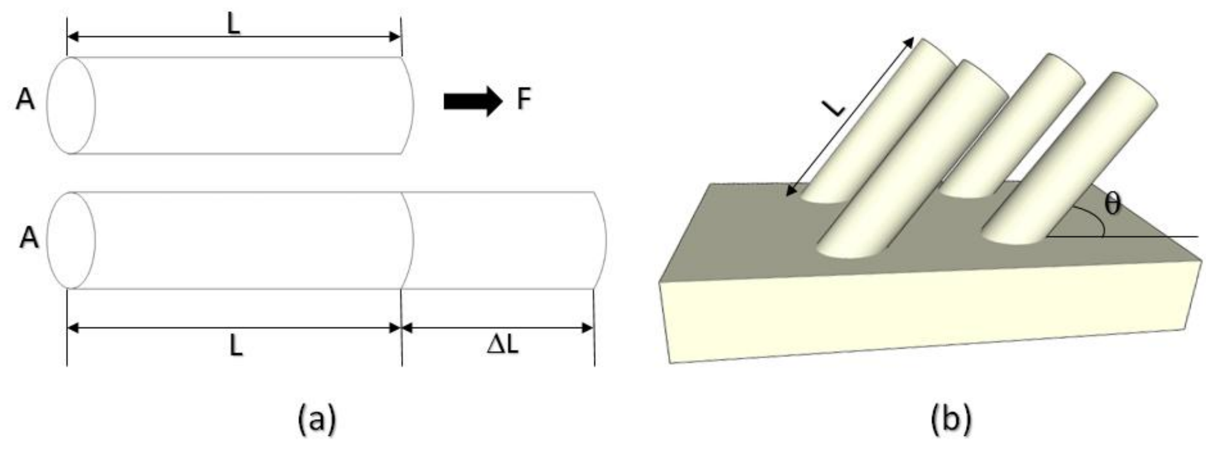
The modulus of elasticity or Young's modulus is a material property that describes the resistance of material to deformation. As is shown in Eq.1, Young's modulus is the ratio of stress,σ, (force F per unit area) to strain ,ε,(the ratio of elongation ,Δl , over the initial length L) .

As is seen in Figure 1, the Young's modulus of a rod with a cross section of A and a length of L under the force of F is expressed by Eq.1.

$$E = {}^{\sigma}/_{\varepsilon} = \frac{{}^{F}/_{A}}{{}^{\Delta L}/_{L}} \tag{1}$$

The Young's modulus is one of the intrinsic properties of any material. If the structure comprises of a combination of hierarchical elements with similar modulus, the overall structure modulus is different from the individual modulus of each element. The overall structure Young's modulus can be referred as effective or apparent Young's modulus. The dependence of the effective modulus on various geometrical and material parameters can be expressed by Eq. 2. The effective parameters on the apparent Young's modulus are d (the pillar diameter), L (the pillar length), AR (the ratio of pillar length to pillar diameter), θ tilting angle (0° <θ < 90°) and ρ (pillar density) [26].

$$E_{eff} = \frac{3\pi E\rho d^2 \cos\theta}{64(AR)^2(\sin\theta)^2}$$



(2)

Figure 1. (a) Deformation of a rod under force *F*, (b) a structure made of multiple rods with length *L* and angle θ

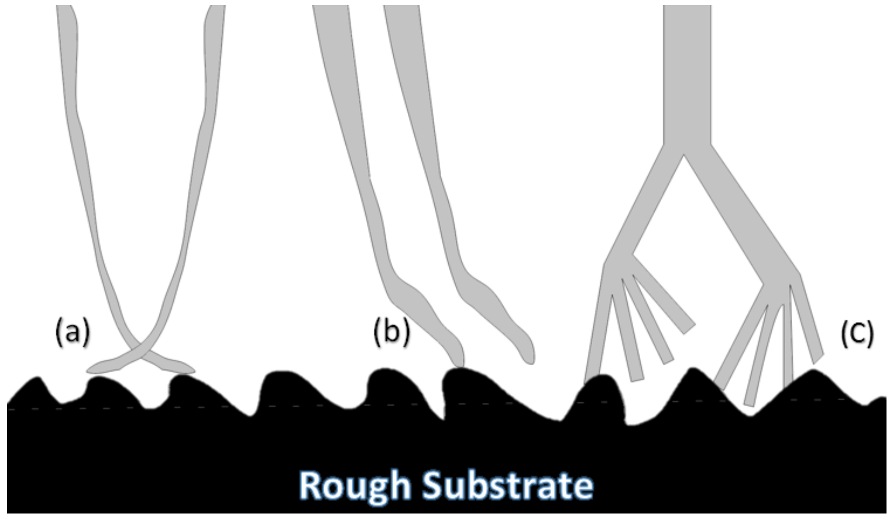


Figure 2. The schematics of various configurations of setae,(a) single-section leg (b) double-section leg (c) multiple-section leg

In which E is the Young's modulus of the individual pillar. Figure 2 shows three different configurations of strings (setae) in the feet mechanism of animals that have different adhesions to rough surfaces. One of the main aims of this paper is to consider the appropriate geometrical arrangement of the setae in order to obtain a reasonable adhesion ability for the proposed skin adhesive patch.

In Figure 2, all three structures shown have the same overall height but different configurations. In Figure 2(a), the configuration consists of two thin setae. The geometry and the obtained stiffness cannot guarantee the slanted position in order to provide appropriate adhesion to a rough surface. In Figure 2(b), the thickness of the legs are not constant and the legs are thicker close to the roots and thinner close to the end. The thick roots guarantee the stability of setae and allow the lengthy legs reach the valleys on a rough surface. However, in this configuration the few number of setae may not be appropriate to provide a reasonable surface adhesion.

In Figure 2(c), the leg is comprised of three main sections. The thick root section can guarantee the stability of the legs. The intermediate section called stem allows maintaining the slanted position of the legs. The end section with multiple smaller setae can provide appropriate adhesion to the rough surfaces. Increasing the number of setae of the end part and reducing their thicknesses leads to formation an appropriate adhesion to the rough surfaces. Therefore, the hierarchical setae in gecko's toe pad can be considered as an efficient structure in providing appropriate adhesion to the rough surfaces [27].

Figure 3 shows different parts of the gecko's toe pad. As can be seen in Figure 3, the gecko's toe pad is comprised of an array of setals that can be considered as cylindrical and elastic rods with a radius of R and a Young's modulus of E. Therefore, the effective Young's modulus of the overall structure can be obtained by Eq. 2 [28].

As shown in Figure 3, the adhesion between the gecko's toe pad and rough surfaces is due to the presence of setae and the spatulae that can play an important role in climbing geckos on different rough surfaces [29]. Seta is made of β-keratin which has a high modulus of elasticity of around 7 GPA [30]. However, the array of setae has a much lower apparent elastic modulus which in turn contributes to a high adhesion to the rough surfaces [28, 31].

The surface cleanliness and geometrical characteristics are important factors affecting the adhesion between two rough surfaces. Unlike gecko's toe pad with self-cleaning mechanism, the adhesive wound dressing can quickly get contaminated by human sweat glands secretion. So, the endurance of adhesive wound dressings can quickly diminish. Under these circumstances, the housefly's appropriate adhesion on contaminated surfaces can be used in order to increase versatility of the proposed wound dressing. In a test on a specific species of housefly, it was found that the fly applies no vertical forces on surfaces in order to acquire stability. The symmetric leg configuration of a housefly provides forces towards the centroid of its body mass and leads to the equilibrium of the insect. Therefore, the insect is able to withstand its weight and stay on the ceiling [32, 33].

Moreover, the housefly has sticky mechanism to adhere to contaminated surfaces. This insect uses the sticky material that is secreted from its gland to increase surface adhesion [34].

Figure 4(a) shows the symmetric configuration of a housefly's legs. The symmetric geometry resulted in better stability on the contaminated surfaces. The placement of the housefly's leg on a surface is shown in Figure 4(b). The adhesion mechanism of the insect leg can be seen in figure 4(c). The ending parts of housefly leg is similar to the gecko's toe pad because both have an ending section named setae which is connected to the spatulae. Further, a layer of adhesive can increase the spatulae adhesion to contaminated surfaces. This can be an appropriate mechanism in increasing the adhesion of the proposed skin adhesive patch to contaminated human skins. These patches should be designed in a way to apply compressive forces on the human skin, so that they may become an appropriate replacement for sutures in order to close the wound gap.

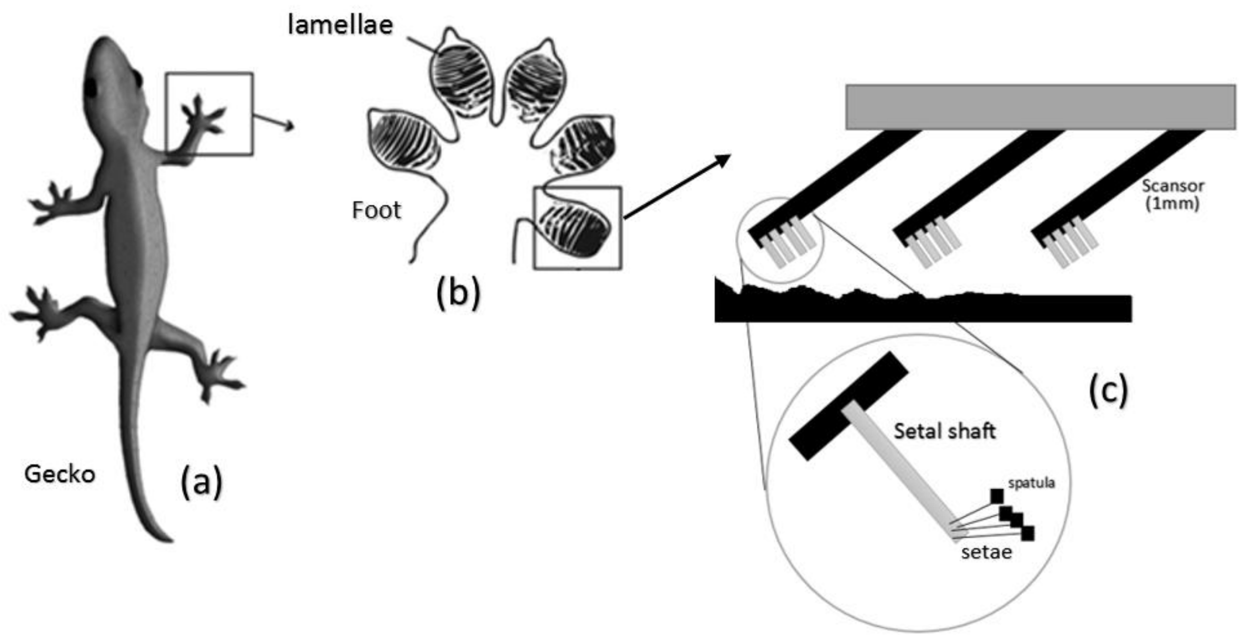


Figure 3. (a) Tokay gecko, (b) The gecko's toe pad (c) micro-scale view of gecko's toe pad

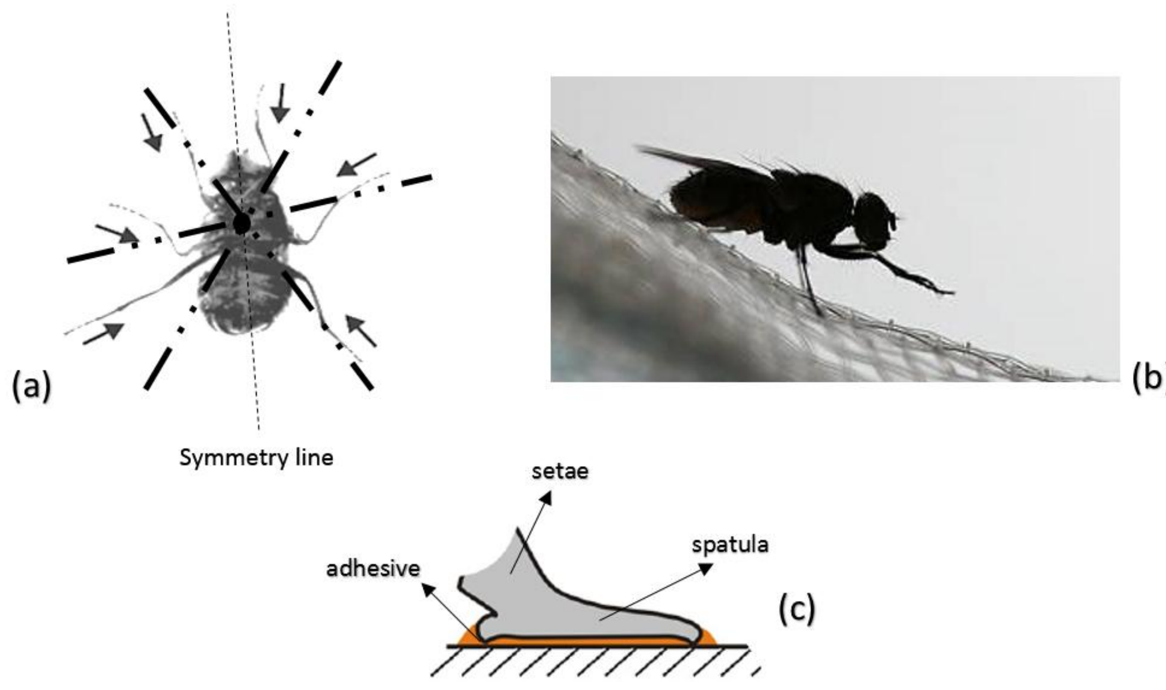


Figure 4. (a) The symmetry of the housefly legs and opposing forces, (b) the placement of the housefly legs on rough surfaces (c) different sections of the housefly leg

By considering the gecko toe's pad mechanism, the proposed skin adhesive patch was comprised of three parts including the patch backing (root), the patch legs (similar to the seta of the housefly) and the ending section that is placed on the human skin. In contrast to the traditional skin adhesive patch, the proposed patch does not fully adhere to the human skin and thus provide effective air circulation in order to aid cells and tissue regeneration by oxygen.
In addition, the symmetrical design inspired by housefly leg can contribute to opposing forces to close the wound. Moreover, the adhesive layer can provide better adhesion to the human skin. The proposed skin adhesive patch is shown in Figure 5.
In Figure 5, the patch backing (shown as (a)) was inspired from gecko toe in order to maintain the leg stability. The thickness of this section is of great importance since it can maintain the slanted position of the legs (shown as (b) in Figure 5). The legs are similar to the setae of gecko toe pad or the housefly setae that connect the patch backing to the ending section of the legs called spatula.
The spatula section (shown as (c) in Figure 5) can adhere to various surfaces. Moreover, the adhesive layer, shown as (d) in Figure 5, was inspired by the sticky mechanism of the housefly legs. This adhesive layer allows the skin adhesive patch to have an appropriate adhesion with contaminated and rough surfaces of human skin.
Several geometrical parameters of the proposed adhesive wound dressing including the leg length (L), the tilted leg angle (θ), the patch thickness (t) and the number of legs (n) were considered for numerical investigations. These geometrical parameters are shown in Figure 6. In order to investigate the effect of different geometrical parameters on the skin adhesive patch, 54 different cases were studied.
The finite element model of the human skin was modeled similar to the natural human skin. As shown in Figure 5, the human skin is comprised of three sections of epidermis, dermis and hypodermis. Epidermis is the upper layer and is in contact with skin adhesive patch. The skin dermis, as the middle layer, contains the blood vessels. The lowest layer of skin is hypodermis. In order to study the influence of the parameters on the wound closure, a gap (f) was considered as shown in Figure 5 as the representative of the wound gap in the human skin.

2.1 Finite element simulation

In this paper, Abaqus/standard finite element code was used for numerical investigation of the skin adhesive patch. By using numerical simulations, various geometrical parameters were investigated in order to obtain an appropriate skin wound dressing.
The finite element model for the proposed skin adhesive patch is shown in Figure 7. Three parts of the patch including the backing, the leg and the spatula are modeled as elastic materials.
For modeling the adhesive layer between the patch and human skin the cohesive elements governed by a bi-linear traction-separation law were used. Three-dimensional analyses are time consuming especially when several parameters are to be studied. In order to reduce the computational time, two-dimensional plane strain model was utilized. As mentioned, the human skin is composed of three layers of epidermis, dermis and hypodermis each one with different properties [35]. After defining input parameters, boundary conditions were determined as shown in Figure 7.
In order to keep the skin connected to other parts of the human body, the end of the hypodermis was constrained in the horizontal and vertical directions. A tensile distributed load was applied to the both left and right sides of the skin part covered by the patch to mimic the opening force applied on the wound. Therefore, the numerical model was aimed to assume the actual conditions applied on the human skin.
In finite element simulations, mesh convergence study was undertaken to ensure about the appropriate number of elements. For this, the element size was changed and the stress distribution in the middle of patch backing was assessed. It was found that an element size of 1.2 mm was acceptable.

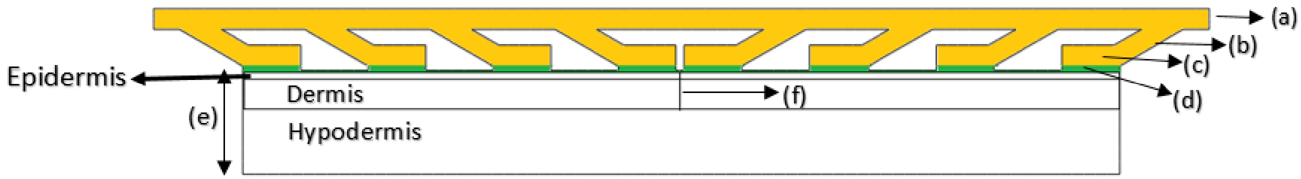


Figure 5. Proposed patch geometry inspired by the two mechanisms of the gecko and housefly feet

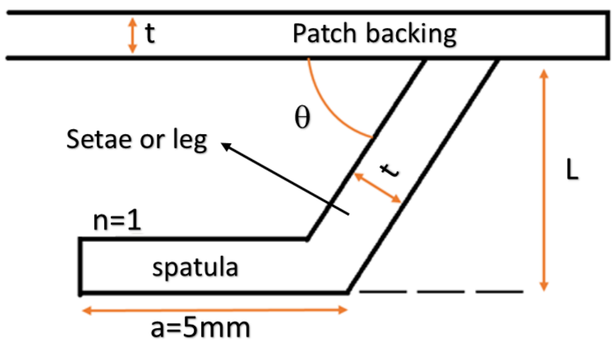


Figure 6. The geometrical parameters of the proposed skin adhesive patch

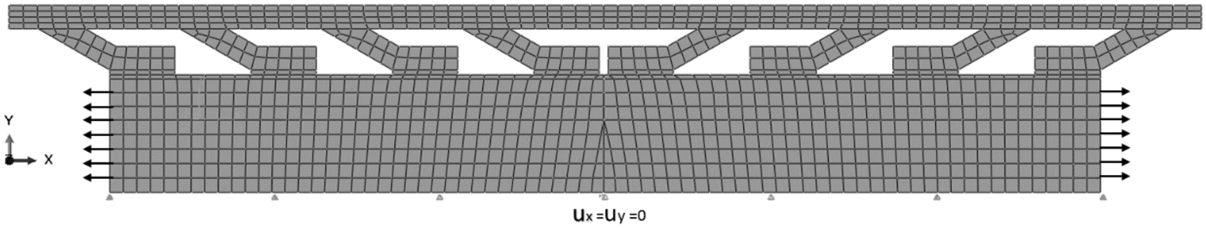


Figure 7. Finite element model of the wound patch and the skin layers

2.2 Effect of geometrical parameters in the proposed skin adhesive patch

The purpose of assessing the effects of various geometrical parameters on the skin adhesive patch performance was to find an appropriate design that not only can close the wound gap completely, but also can tolerate the tensile stresses in the middle of the skin adhesive patch. Therefore, the desirable patch may not mechanically fail from this location and can maintain its strength. Also, it must be noted that the backing thickness in the skin adhesive patch should be a certain amount so it can prevent from high deformation. In order to evaluate the stress distribution in the middle of the skin adhesive patch, path (a-a) was defined as shown in Figure 8.

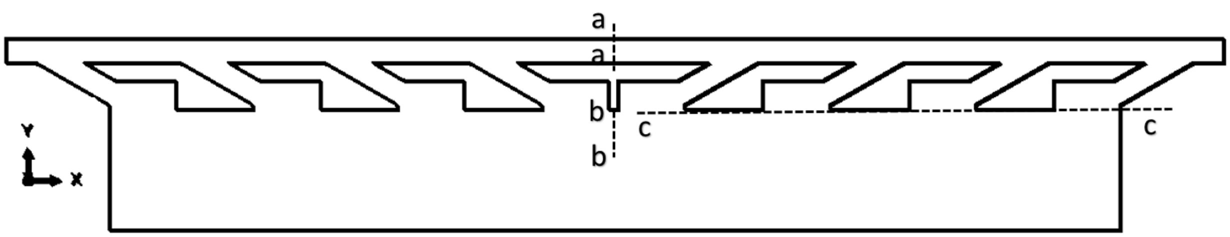


Figure 8. (a-a) Defined path in the middle of the backing skin adhesive patch, (b-b) defined path in the depth of the wound, (c-c) defined path on the skin surface

2.2.1 The effect of leg thickness

In order to simplify the problem, the thickness of the adhesive patch backing leg and spatula were considered the same. By evaluating the tensile stress value in the middle of the patch backing and changing the geometrical parameters, an appropriate skin adhesive patch design can be achieved. In Figure 9, the effect of leg thickness is studied on the normal stresses in the middle of the adhesive patch backing. It can be seen in Figure 9 that amongst the leg thicknesses studied in this paper two thicknesses of 0.5 and 2 mm resulted in lower stresses of the patch backing compared to the thickness of 1 mm. The high tensile stress value in the patch backing can give rise to the patch rupture from the middle. Therefore, a patch with 1 mm thickness may be more likely to encounter failure against the applied force.

The lower stress values in the patches with the thicknesses of 0.5 and 2 mm were caused by two different reasons. The adhesive patch with 2 mm thickness had the ability to withstand against tensile stress that is evident from the structural stability shown in Figure 10(a). The skin adhesive patch structure can tolerate against the applied stress to skin. Therefore, lower tensile stress was induced in the middle of the adhesive patch with 2 mm thickness. In contrast, the adhesive patches with thicknesses of 0.5 and 1 mm, was not strong enough to bear the tensile stress and thus underwent large deformations due to insufficient thickness in the patch backing and legs, as shown in Figure10 (b) and (c). Therefore, in these cases the adhesive patches were not capable of closing the wound edges and yet the adhesive patches deformation caused the wound to open further. Hence, the wound patches with thicknesses of 0.5 and 1 mm are not suitable for closing the skin wound. However, the adhesive patch with 1 mm thickness endues higher tensile stress in its backing compared to the adhesive patch with the thickness of 0.5 mm as due to the thicker legs in the patch with the thickness of 1 mm transferred higher portion of the applied force to the patch backing.

Moreover, in order to further study the performance of the skin adhesive patch, the displacement of the wound edges was also studied. The wound gap induced in human skin should be fully closed so that two edges of the wound can reach each other. However, excessive pressure applied on the wound edges may not be suitable as it can give rise to unsuitable scar formation on the wound location after healing.

In order to study the wound closure as a result of using the skin adhesive patch, the wound opening displacement was assessed. The schematics of fully closed and unclosed wound are shown in Figure 11. The wound opening displacement versus the leg thickness curves are shown in Figure 12 for different number of legs and leg angles. These results were obtained for the skin adhesive patches with the vertical leg length of 6 mm and with three different leg angles of (30, 60, 90) and the number of legs of 8, 6 and 4. It should be mentioned that the wound gap before closing by the adhesive patch was considered 0.02 mm. As shown in Figure 12, only backing thickness of 2 mm can fully close the wound gap.

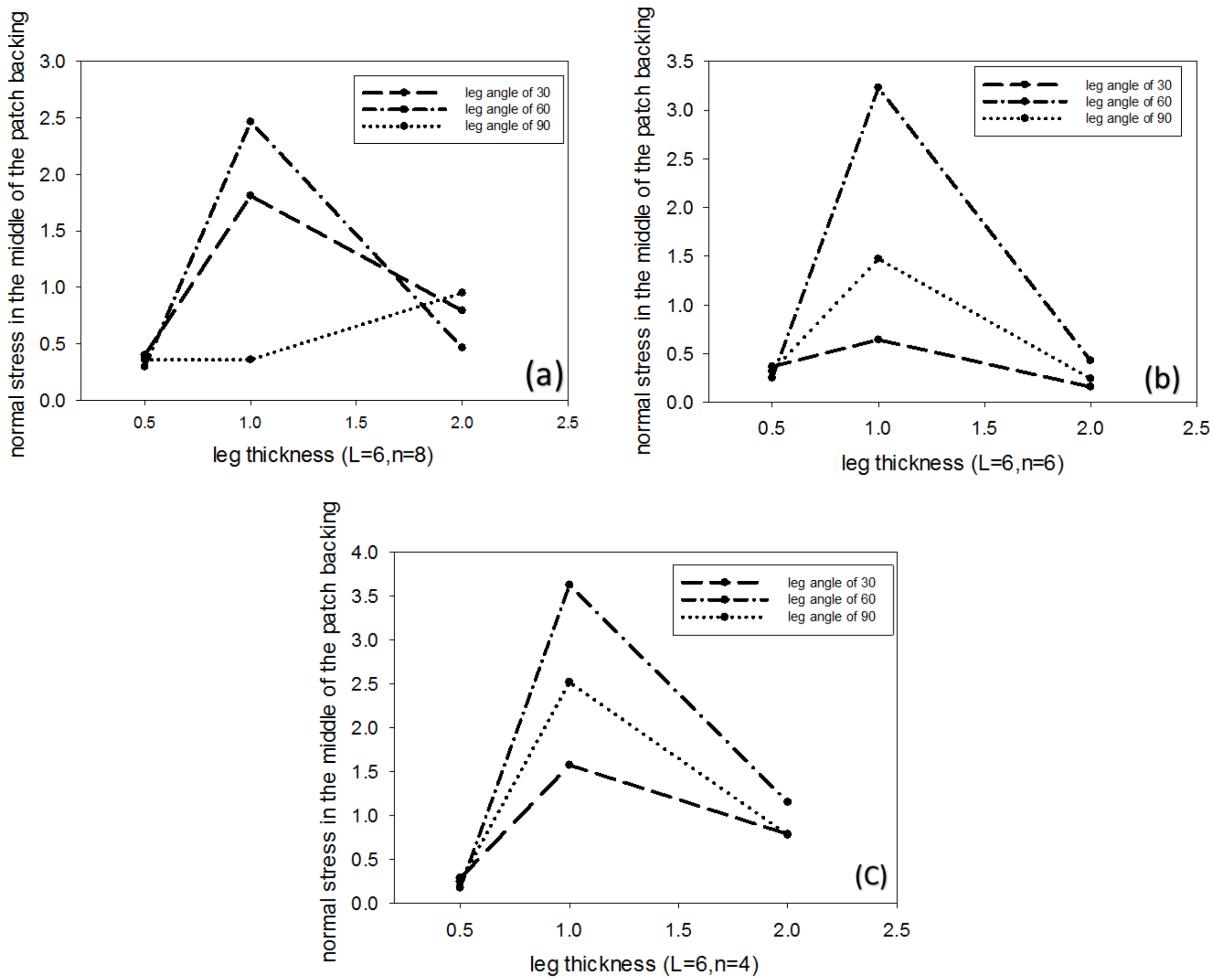


Figure 9. The maximum longitudinal normal stress in the middle of the patch backing with respect to the leg angle for adhesive patches with different leg thicknesses and number of legs

The leg thickness can be considered as an important parameters in providing slanted position of legs and consequently in providing appropriate contact of legs with rough surfaces. Therefore, amongst the leg thicknesses considered in this study, the thickness of 2 mm is suitable. The patch with the leg thickness of 2 mm not only has less stress in the middle of the patch compared to the other two thicknesses, but also can close the wound appropriately.

2.2.2 Effect of the number of legs on the wound's edge displacement

Figure 13 shows von-misses stress contour plots for patches with 4, 6 and 8 number of legs. The number of legs can change the stress distribution of skin considerably. By reducing the number of legs and maintaining the other parameters constant, the resisting force exerted from the adhesive patch legs on the skin against the applied external load can cause high local stress values and causes more stress concentration on the wound location of the skin and that makes the wound more open.

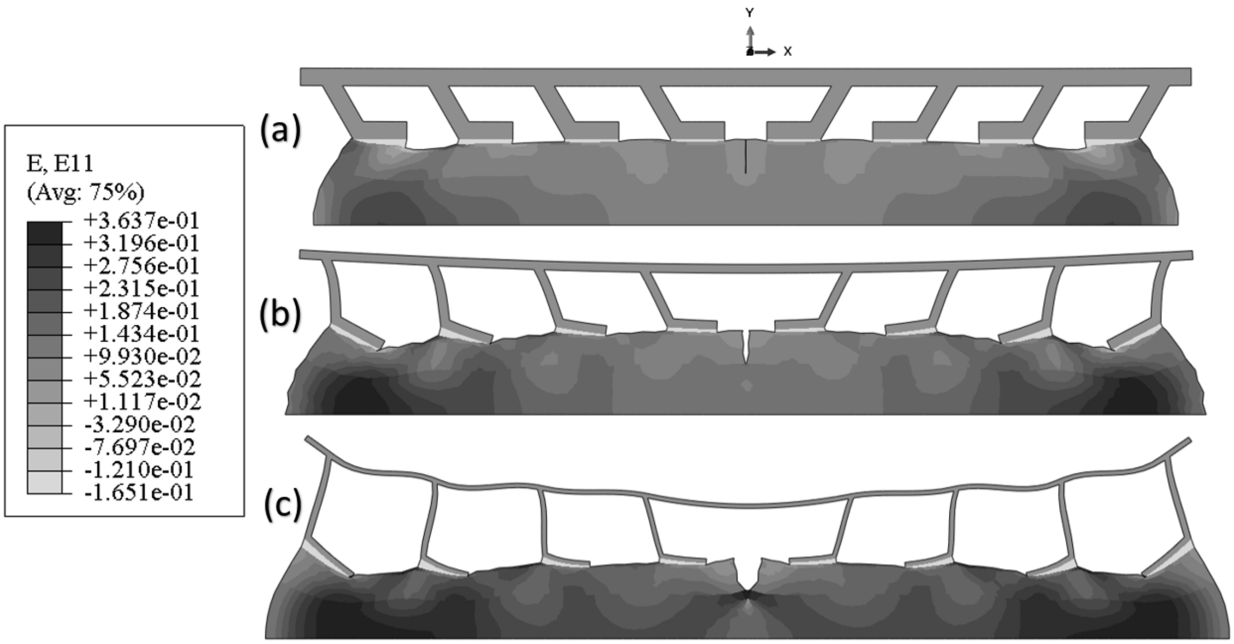


Figure 10. Strain contour plot for the skin adhesive patches with thicknesses of (a) 2 mm (b) 1 mm and (c) 0.5 mm

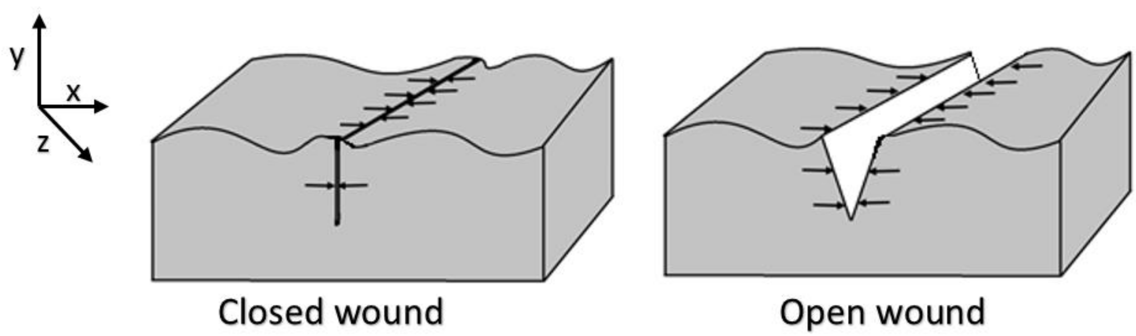


Figure 11. Schematics of the fully closed and open wounds

Figure 14 shows the wound opening displacement versus the number of legs for the adhesive patch with different leg angles. As can be seen in Figure 14, using fewer number of legs for the adhesive patch may not resist against wound opening by the applied external load and thus number of legs can play an important role in closing the wound's gap. Using eight legs was found to be adequate for closing the wound's gap by the applied force. However, it can be concluded that by knowing the applied load magnitude, the required number of legs can be determined from finite element analyses. This behavior is similar to the insects when trying to adhere to rough surfaces. Heavier insects need more legs to be stationary when walking. This allows them to apply more adhesion forces against forces which causes separation [36].

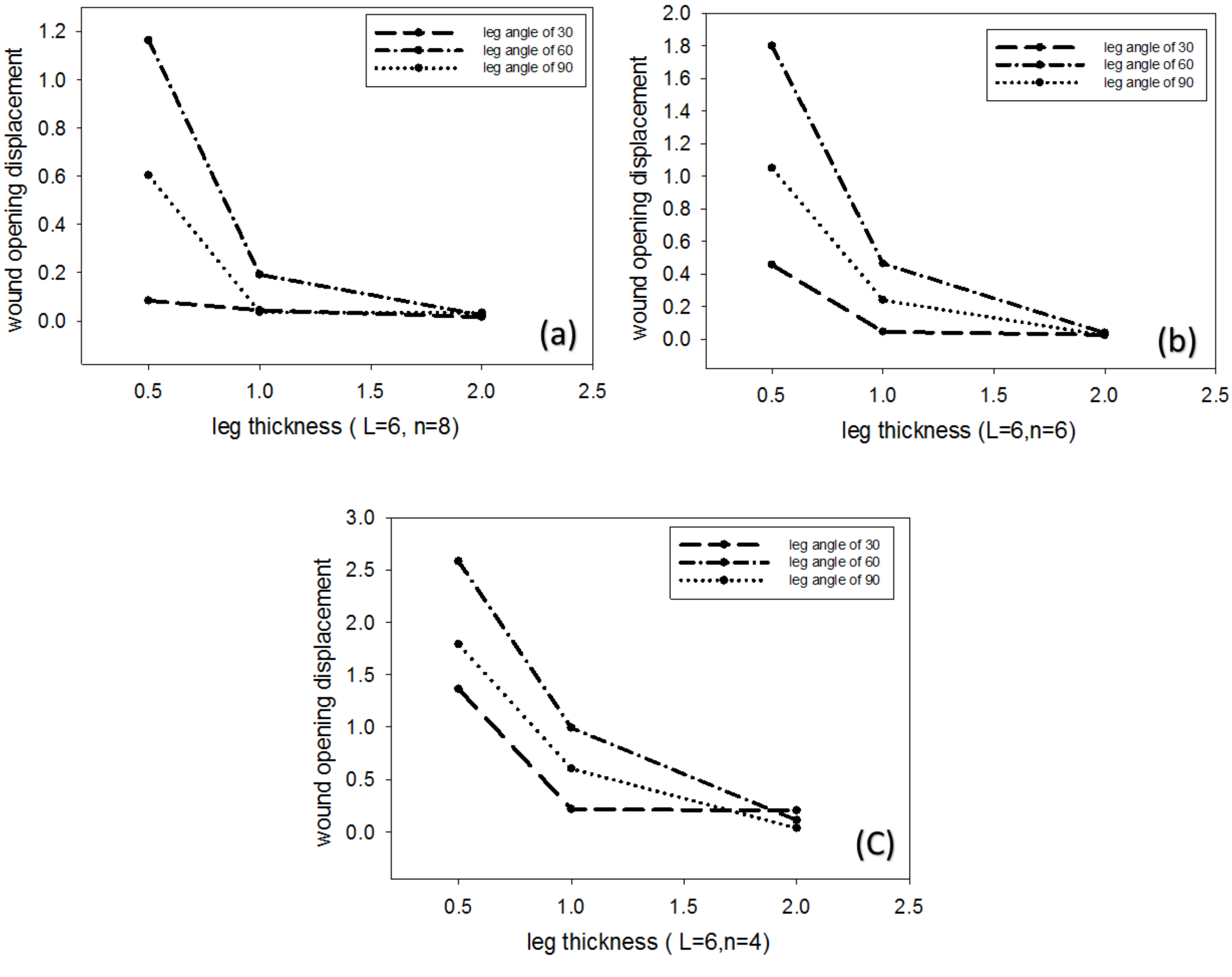


Figure 12. The wound opening displacement versus the leg thickness for three leg angles of 30°, 60° and 90° and a leg length of 6 mm

2.2.3 Effect of leg angle

Another important parameter influencing the stability of the skin adhesive patch is the leg angle. Determining the proper leg angle for the proposed skin adhesive patch can provide an appropriate pressure throughout the depth of wound causing the complete wound closure. Therefore, in order to determine the effect of leg angle on the performance of the proposed skin adhesive patch in closing the wound, the contact stress distribution along the wound edges was assessed. This parameter represents touching two edges of wound. The zero contact stress value in some portions of the wound edges indicates the openness of some part of the wound and thus shows patch inefficiency. In order to determine this parameter, a path was defined along the wound edge as shown by b-b in Figure 8.

According to Figure 15 for the adhesive patch with the leg angle of 30^{o}, the first part of the patch is unclosed. As the contact stress value for the initial part of the wound was zero. Therefore, the skin adhesive patch with 8 legs, 2 mm thickness and the leg angle of 30 degree cannot completely closed the wound giving rise to delay in wound healing.

Amongst the angle of legs considered in this study, only the angle of 60^{o} resulted the complete wound closure. It can be seen in Figure 15 that the adhesive patch with the leg angle of 60^{o} could completely close the wound gap as the contact stress value along the wound edge was non-zero.

Moreover, the increasing value of the contact stress by progressing into the wound depth, as seen in Figure 15 for the adhesive patch with leg angle of 60^{o} can be useful as more pressure is required for the depth of the wound compared to the outer skin surface. The lower contact stress applied by the adhesive patch on the outer skin surface can reduce the chance of keloid formation after healing.

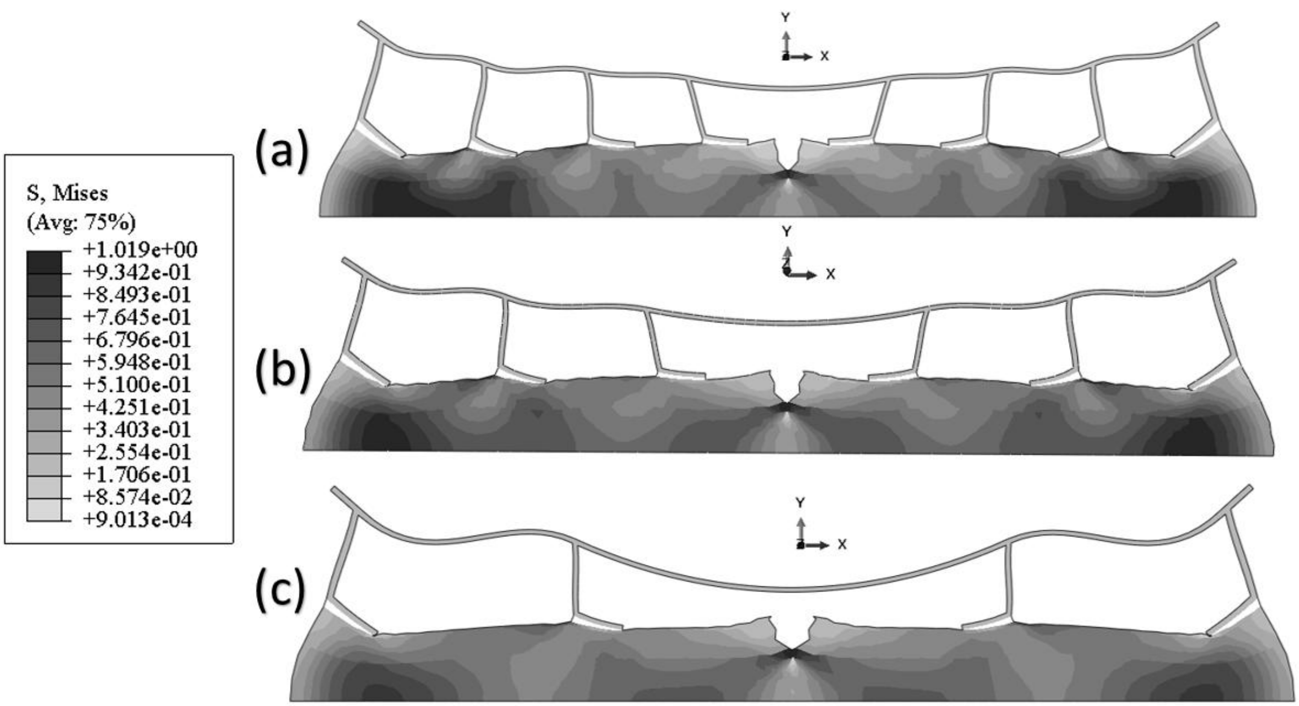


Figure 13. Von-misses stress contour plot for patches with number of legs of 4, 6 and 8 and a leg thickness of 0.5 mm

2.2.4 The effect of leg length

As mentioned in section 2.2.3, patches with the thickness of 2 mm, 8 legs and with the leg lengths of 6 and 7 mm can fulfill the adhesive patch requirement. The proposed adhesive patch structure should resist the applied tensile stress and prohibit the patch backing failure. Therefore, if lower value of the stress is induced in the adhesive patch backing, the load bearing capacity of the patch can be improved. It was founded from the FE results that changing the leg length from the 6 to 7 mm, decreased the maximum normal stress induced in the middle of the adhesive patch backing by 57%.

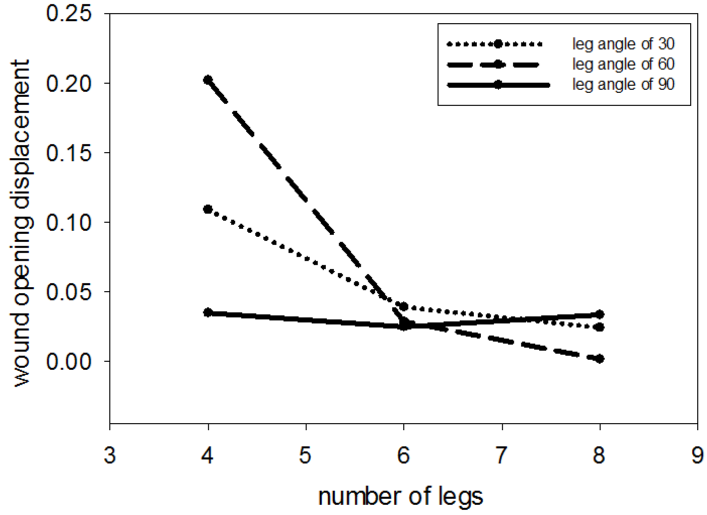


Figure 14. The wound opening displacement versus the number of legs

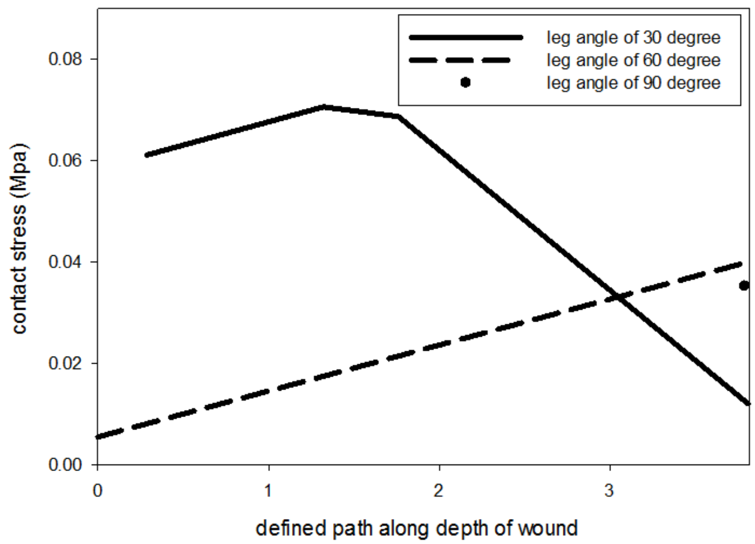


Figure 15. Contact stress versus defined path along depth of wound for skin adhesive patches with 8 legs, 2 mm thickness and leg angle of 30, 60 and 90 degrees

2.3 Comparison between the proposed and traditional skin adhesive patches

To ensure the effectiveness of the proposed skin adhesive patch in wound closure, a path (c-c) was defined on the skin as shown in Figure 8. The tensile stress diagram in X-direction was plotted based on length of defined path. Figure 16(A) shows the longitudinal normal stress in the traditional adhesive patch and the proposed skin adhesive patch with an angle of 60o. In Figure 16(B), the normal strain contour along the skin path for the skin adhesive patch was shown in X-direction. Section (a) in Figure 16(B) was assigned to the first leg after the wound gap. As shown in Figure 16(B), each leg applied two compressive forces on both sides of the leg causing the skin to be stretched underneath each leg. By approaching to the end of the patch, the applied tensile stress areas changed considerably. These changes are obvious in sections (c) and (d) of Figure 16(B).

The traditional patches apply uniform stress along the skin. As shown in Figure 16(C), one of the main problems of using traditional adhesive patch is the continuity of the adhesive layer that leads to increased moisture entrapped under the adhesive patch and provide lack of air circulation. The lack of sufficient stability and the requirement for substitute the skin adhesive patch due to the contamination of human skin make traditional patch less effective. In addition, traditional patches create mechanical irritations on the patient's skin. These irritations caused by removing of the adhesive repeatedly from the patient's skin that leads to patient dissatisfaction and may cause skin tearing in elderly patients due to their skin sensitivity.

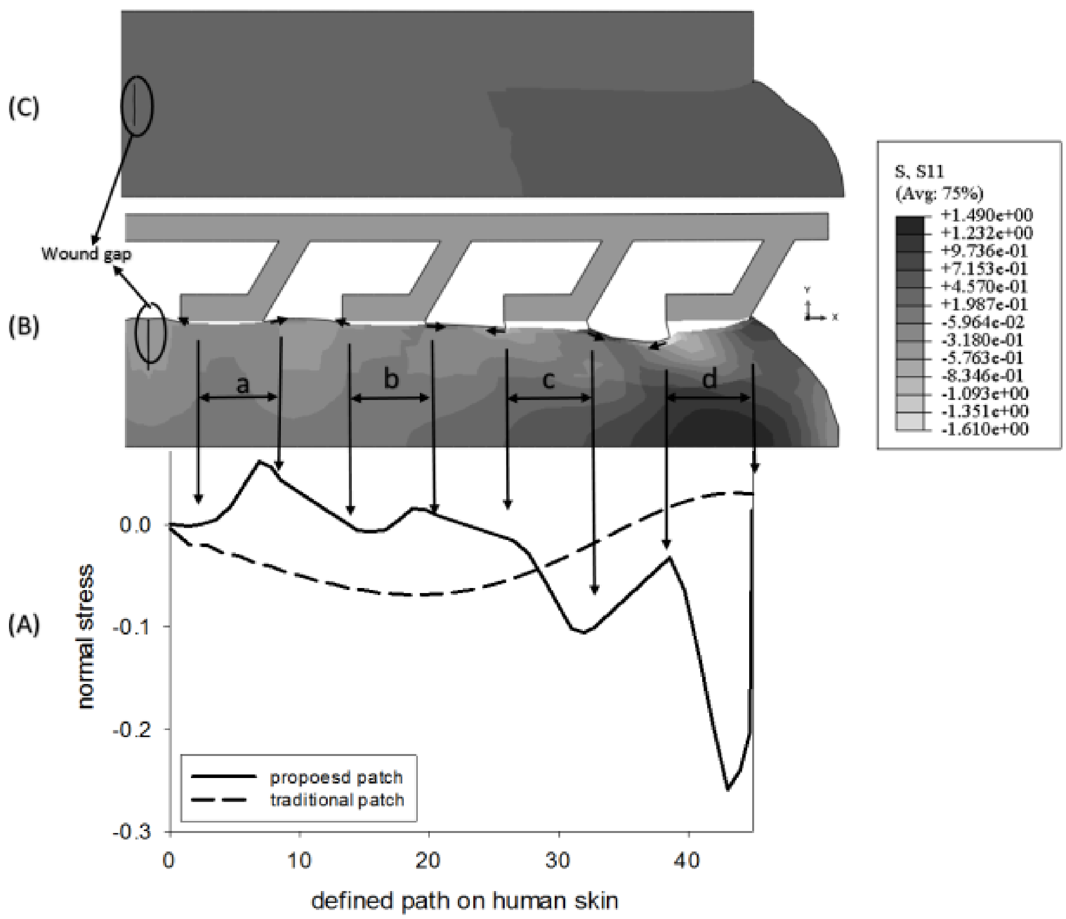


Figure 16. (A) Normal stress versus defined path on human skin in the traditional and proposed skin adhesive patch, (B) normal stress contour in the proposed skin adhesive patch (C) normal stress contour in the traditional adhesive patch

Therefore, the proposed skin adhesive patch with 8 legs, 60º leg angle and 2 mm thickness is the most appropriate structure for the skin adhesive patch. It can decrease the effect of the tensile stress around the wound and apply desired compressive forces in the wound gap in order to completely close the wound.

3.Result

An appropriate method of closing wound should be easily applicable, quick and with minimum pain. The skin adhesive patch proposed in this paper inspired from the gecko toe pad and housefly legs. Several geometrical parameters of the proposed adhesive wound dressing including the leg length, the tilted leg angle, the patch thickness and the number of legs were considered for numerical investigations. The effect of different geometrical parameters were assessed on the skin adhesive patch such as normal stress in the middle of patch backing, wound opening displacement and contact stress.

The leg thickness was found to be an important parameter in maintaining the slanted position of the legs and consequently in providing appropriate contact of the spatula with rough surfaces. By considering the normal stress in the middle of patch backing and wound opening displacement skin adhesive patches with 2 mm thickness can maintain the patch strength against the tensile stress applied to the human skin. The other important parameter was the number of legs that can play an important role in closing the wound gap. By increasing the number of legs, the total distributed resisting force applied on the skin increased. Therefore, skin adhesive patch with eight legs was found to be adequate for closing the wound gap in comparison with the number of legs of 6 and 4.

4. Discussion

The effect of leg angle on the performance of the proposed skin adhesive patch was assessed. It was found out that the adhesive patch with the leg angle of 60° could completely close the wound gap as the contact stress value along the wound edges was non-zero. It was founded from the FE results that 7 mm leg length can decrease the maximum normal stress induced in the middle of the adhesive patch backing considerably.

Conflicts of interest

The authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest, or non-financial interest in the subject matter or materials discussed in this manuscript.

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