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Skin friction blistering: computer model

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Background/purpose: Friction blisters, a common injury in sports and military operations, can adversely effect or even halt performance. Given its frequency and hazardous nature, recent research efforts appear limited. Blistering can be treated as a delamination phenomenon; similar issues in materials science have been extensively investigated in theory and experiment. An obstacle in studying blistering is the difficulty of conducting experiment on humans and animals. Computer modeling thus becomes a preferred tool.

Method: This paper used a dynamic non-linear finite-element model with a blister-characterized structure and contact algorithm for outer materials and blister roof to investigate the effects on deformation and stress of an existing blister by changing the friction coefficient and elastic modulus of the material in contact with the blister.

Results: Through the dynamics mode and harmonic frequency approach, we demonstrated that the loading frequency leads to dramatic changes of displacement and stress in spite of otherwise similar loading. Our simulations

show that an increased friction coefficient does not necessarily result in an increase in either the stress on the hot spot or blister deformation; local maximum friction stress and Von Mises stress exist for some friction coefficients over the wide range examined here. In addition, the stiffness of contact material on blistering is also investigated, and no significant effects on deformation and Von Mises stress are found, again at the range used. The model and method provided here may be useful for evaluating loading environments and contact materials in reducing blistering incidents.

Conclusion: The coupling finite-element model can predict the effects of friction coefficient and contacting materials' stiffness on blister deformation and hot spot stress.

Key words: friction – blisters – bullae – models – man

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SKIN FRICTION blisters, a frequent dermatology injury associated with intensive abrasion of skin against other surfaces, can inactivate an otherwise healthy individual, and be of significant consequence for such intensive events as athletics, military operations; for infantry soldiers carrying heavy equipment and supplies over long distances, blisters can account for 48% of the total injuries (1).

From a mechanical approach, abrasion will lead to “sore spots”, portion of the skin undergoing excessive stress and strain, and finally results in blistering (2). Actually, the blisters are caused by the frictional forces that mechanically separate the surface epidermal cells from the stratum spinosum (3). Hydrostatic pressure then causes the area of separation to fill with a fluid similar in composition to plasma but with a lower protein level (4) (see Fig. 1).

In the late 1950s and the early 1970s (3, 5–8), friction blister became a focus of skin research and a special apparatus was designed for creat-

ing friction blisters. The instrument consists of a rubbing head to which various materials (including textiles) could be firmly attached. The head could be moved over the surface of any chosen skin site at a selected stroking rate under a given compressive load. The effect of skin moisture was also studied; a dry or near-dry skin reduced the friction; intermediate degrees of moisture increased friction; and highly moist or completely wet skin decreased the friction again.

The rubbing head geometry, weight and attached material all affect the friction coefficient measurements (9). Sivamani et al. (10, 11) utilized the UMT Series Micro-Tribometer (UMT, Campbell, CA, USA), a tribology instrument that permits real-time monitoring and calculation of the important parameters in friction studies, to conduct tests on abdominal skin samples of four healthy volunteers. They concluded that skin friction appears to be dependent on additional factors – such as age, anatomical site and skin hydration; the choice of the probe and the test



Fig.1. Friction blister on skin. The shear and normal force separate the mid- or upper malpighian layer with roof composed of stratum corneum, stratum granulosum, and a small segment of amorphous cellular debris (3).

apparatus also influences the measurement (10, 11), and Amonton's law does not provide an accurate description for the skin surface (12).

Emollients and antiperspirants alleviated blistering. For instance, Darrigrand et al. (13) and Reynolds et al. (14) showed that antiperspirants reduced sweat rates and tended to decrease blisters, in spite of their side effect of introducing irritant dermatitis. Yet, antiperspirants with emollients abated irritant dermatitis but did not reduce total foot-sweat accumulation, blister or hot spot incidence, or blister severity, for the emollients may have altered the antiperspirant's chemical properties. In addition, the emollients may have acted as moisturizing agents, thus increasing the friction (15), and macerate the stratum corneum (16).

Clothing effects on blistering have also been documented. Herring and Richie (17) conducted a double-blind study to determine the effect of sock fiber composition on the frequency and size of blistering events in long-distance runners. Between two otherwise identical socks, except fiber contents, (i) 100% acrylic, (ii) 100% natural cotton, the acrylic fiber socks were associated with fewer blisters and smaller blister sizes compared with cotton socks.

An ulcer formation hypothesis (18) can also be applied to the blister forming from mechanical perspective. The plantar foot experiences a distributed shear and compressive stresses due to joint tangential and vertical forces. As a result, the affected skin may slip (i) towards, (ii) away from or (iii) parallel to (i.e. a region that does not slip) each other. Coefficient of friction is defined as the ratio of the tangential/vertical forces, and blister is inhibited if the frictional coefficient is below a critical minimum ($\mu_{R \min}$).

Despite extensive friction blister studies, the prevalence or severity of friction blister remains difficult to predict and prevent. The reasons may lie in the variations of skin condition (surface roughness, hydration, adhesion between skin layers, etc.) among individuals as well as among different anatomic sites of the same person (19). These variations may have pronounced effects on the dynamic contact of skin against outer materials, and finally dictate the blister status.

This paper develops a blistering model by means of the finite-element method. For given shear and normal forces, this model is able to account for the influences of friction coefficient, abrasion material stiffness, non-linear dynamic contact between skin and the material and even the blistering geometry. The blister static and dynamic responses are obtained through mode frequency, and sweeping frequency harmonic analysis, and highly non-linear contact dynamics. The stresses on the hot spots are also compared to account for the effects of friction coefficients and material stiffness.

Model and Material Properties

Blister geometry model

The blister in the model consists of three parts: (i) roofed skin, (ii) blister fluid and (iii) basal cell layer. The roofed layer is composed of stratum granulosum, stratum corneum and a small segment of amorphous cellular debris (3). The blister is considered as an ellipsoid shape with a circular base, whose radius is viewed as the longer axis and set as 3 mm, and the height of the blister is the shorter axis. We simulated the dynamics of the blister model in an ANSYS system (v.10.0, ANSYS Inc., Canonsburg, PA, USA).

The thickness of the roofed skin is 55 μm with reference to the thickness of the sole's stratum corneum (20). The sole basal skin layer thickness is 1.6 mm from the surface measured by ultrasound (20 MHz) (21). The blister fluid is contained in the cavity by roofed skin and the basal skin layer. During the computation, the lateral surface (3D) or sides (2D) of basal skin layer are given displacement constraints.

Material properties

The elastic modulus of roofed skin is about 13 MPa measured using the *in vivo* dynamic (sonic) method (22), and the skin is assumed to

be isotropic. For a steady or transient time span (a time much shorter than the skin relax time) simulation, a linear elastic constitutive behavior can be assumed. The Poisson ratio is taken as 0.4 (23). The blister fluid is more or less like the plasma derived from blood with bulk modulus: 2150 MPa and apparent viscosity: 1.1×10^{-9} MPa s (5).

Contact algorithm

Materials contact skin with different friction coefficients, and the effects on blister are highly significant (17, 24). Such contact is an extremely non-linear dynamic problem. The augmented Lagrange algorithm is used to cope with the challenges by using the Lagrange multipliers or penalty algorithm. So the total potential energy (virtual work) of the system can be expressed as (25, 26),

$$\delta\Psi = \int_{\Gamma} [(\lambda_N + \epsilon_N g_N)\delta g_N + (\lambda_T + \epsilon_T g_T)\delta g_T] dA \tag{1}$$

where λ_N and λ_T are the Lagrange multipliers, ϵ_N and ϵ_T are the associated penalty parameters and δg_N and δg_T are the virtual displacements. The subscripts N and T denote the normal and tangent directions, respectively. Equation (1) can be considered as a generalization of the Lagrange

TABLE 1. Modal natural frequencies for model from first to sixth order to account for resonance frequency

| Order | 1st | 2nd | 3rd | 4th | 5th | 6th |
|----------------|-------|-------|-------|-------|-------|-------|
| Frequency (Hz) | 28.38 | 30.61 | 30.64 | 30.74 | 32.44 | 34.66 |

The lowest frequency 28.38 Hz is far more than in sports competition.

multiplier method where an additional term involving the contact tractions is added to the variational equation.

Result

The model thus designed is executed as a 3D model with a 0.5 ratio of radius. The mode natural frequencies calculated are shown in Table 1, and detailed descriptions on the mode and harmonic analysis are provided in ‘Discussion’. The lowest modal frequency is 28.38 Hz with a modal shape (resonance) shown in Fig. 2.

Figure 3A and B shows the model harmonic analysis with sweeping frequency from 1 Hz to 7 Hz. The loads are 0.1 and 0.01 N, respectively, along the normal and tangential directions on the tip of the blister. From the figures, the maximum displacement at 1.6 Hz is 0.031 mm in Fig. 3A, less than 0.46 mm at 6 Hz in Fig. 3B.

To account for the effects on blistering of material properties in terms of the contacting friction coefficient and stiffness, we simplify the

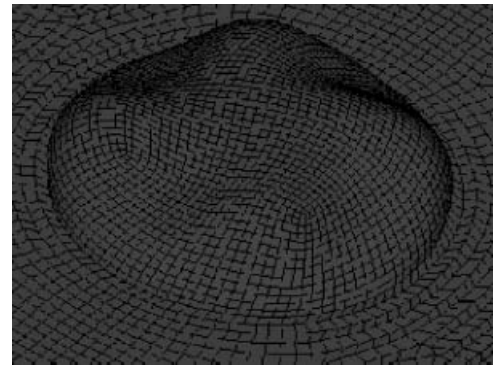


Fig.3. First-order modal shape with frequency 28.38 Hz. When the loading frequency reaches this value, the blister shape will be excited.

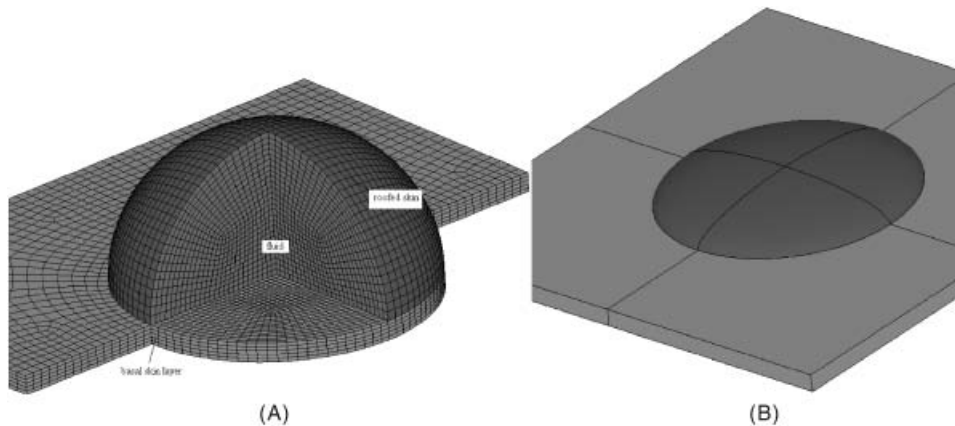


Fig. 2. The 3D blister with different radius ratio (A) 0.9 with finite element, (B) 0.2 in solid model.

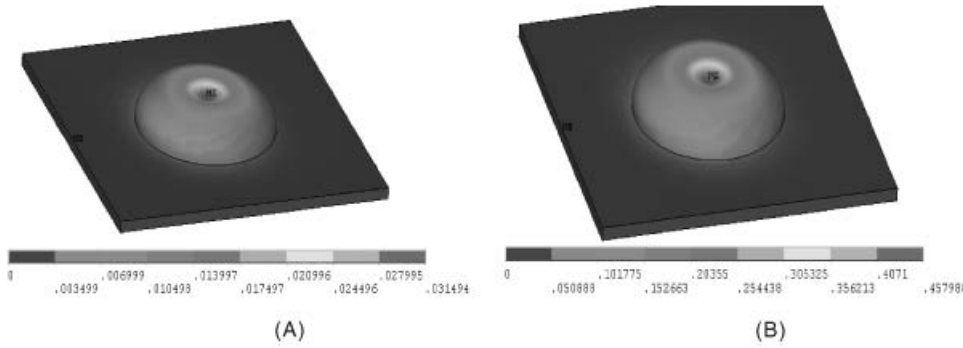


Fig. 4. The displacement of the blister at different frequencies of the excitation (A) 1.6 Hz and (B) 6 Hz. Blister displacement increased in response to rising moving frequency from 1.6 to 6 Hz.

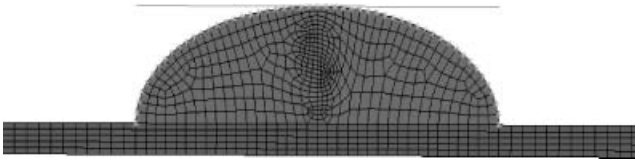


Fig. 5. A 2D Finite-element model of blister. The blue stands for the contacting materials, red for blister fluid, the purple for the basal skin layer, and the yellow for the potential contact element of roofed skin to contacting material. When fore or displacement is loaded on the contacting material, blister will be formed. Different friction coefficient and contact stiffness could be compared.

blister into a 2D finite-element model with a radius ratio of 0.5 (Fig. 4) for facile illustration.

In the 2D model, line elements are used for the roofed skin and contacting material domain, the fluid elements are used in the blister fluid domain and the plane elements are in the basal skin layer. To maintain displacement continuity, displacement-constrained equations are applied to the interfaces between the roofed skin and blister blood, blister fluid and basal skin layer, respectively.

Two equal compressive forces are applied at both ends of the contacting material in the vertical direction. We assume the displacement at the two ends of the basal skin layer to be constrained. The contact algorithm is used to study the interactions between the contacting material and roofed skin. The contacting materials have an elastic modulus of 100 MPa and Poisson's ratio of 0.3. The two compressive forces are 0.1 N each and a 1-mm horizontal displacement is added to the contacting material to generate a friction movement. The blister responses are obtained with frictional coefficient at 0 (frictionless), 0.1, 0.2, 0.3 and 0.4, respectively, as shown in Fig. 5.

The maximum tangential friction stress τ_m and normal pressure P_n occurred on the top contact point of the blister shown in Table 2.

TABLE 2. Maximum tangential friction stress (τ_m) and normal pressure (P_n) at different friction coefficient

| μ | 0 | 0.1 | 0.2 | 0.3 | 0.4 |
|----------------|-------|-------|-------|-------|-------|
| τ_m (MPa) | 0 | 0.069 | 0.044 | 0.050 | 0.053 |
| P_n (MPa) | 0.175 | 1.548 | 0.852 | 0.843 | 0.840 |

τ_m and P_n are critical to blister formation. In order to compare the effect of the friction coefficient, τ_m and P_n are calculated.

With the same friction coefficient 0.1 and the same compressive loads, the elastic modulus of contacting materials changes to 80, 100, and 120 MPa; the respective results of Von Mises stress in the hot spot and displacement of blister show no significant changes so that only the case of 120 MPa is given in Fig. 6 and 7.

Discussion

Frictional blisters, which is a common problem in long-distance running (27) and infantry road march (1), underlie the significance of understanding the dynamic response of body skin under intensive loading. Based on the numerical model, the eigen equation for the system can be established as

$$[K][\phi] - [\lambda][M][\phi] = [0] \quad (2)$$

where $[K]$, $[M]$, $[\lambda]$ and $[0]$ are, respectively, the stiffness matrix, mass matrix, eigenvalue matrix, corresponding mode shape matrix and null matrix of the finite element assemblage (28).

We first computed the natural frequency of the skin system by finding the eigenfrequency from Eq. (2), as this frequency closely relates to the resonance, which arose due to the coincidence between the natural and the loading frequencies and leading to much greater deformation and stress, finally resulting in broken blisters.

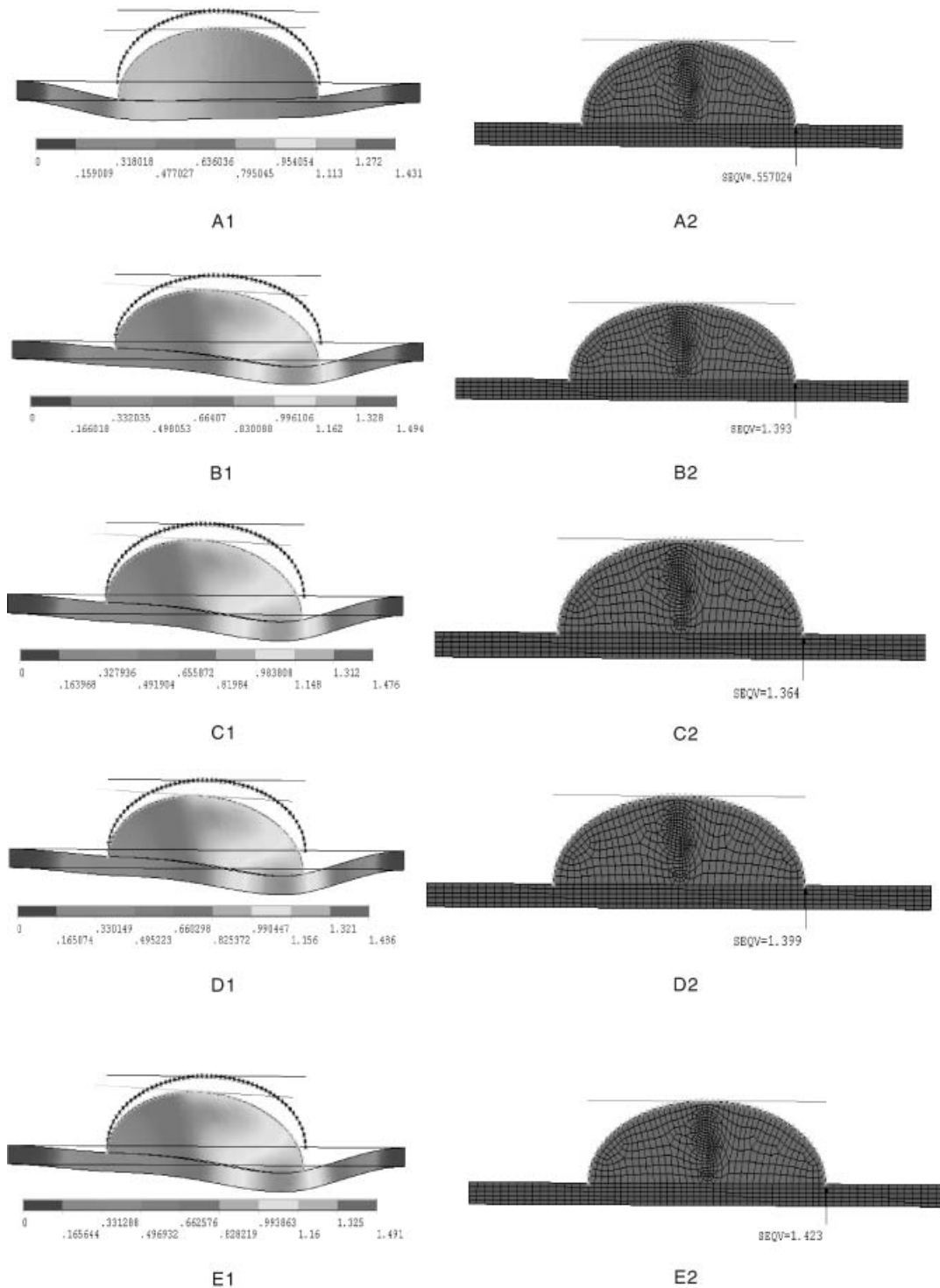


Fig. 6. The displacement and hot spot stress at five friction coefficient levels. From A–E with subscript 1 shows blister displacement, Von Mises stress of the hot spot with subscript 2 and friction coefficient (A) 0, (B) 0.1, (C) 0.2, (D) 0.3 and (E) 0.4. The effect of friction coefficient on blister displacement and stress can be compared.

We assume that the gait frequency is from 1 Hz (normal walk) to 7 Hz (fast run). From the mode analysis result, the 1st-order natural frequency is >20 Hz (Table 1). This means that the loadings with human gait frequency cannot excite reso-

nance, and are consequently unable to lead to the mode shape shown in Fig. 2.

Furthermore, to account for the frequency effects on blistering, a normal force 0.1 N and tangential force 0.01 N were loaded on the top

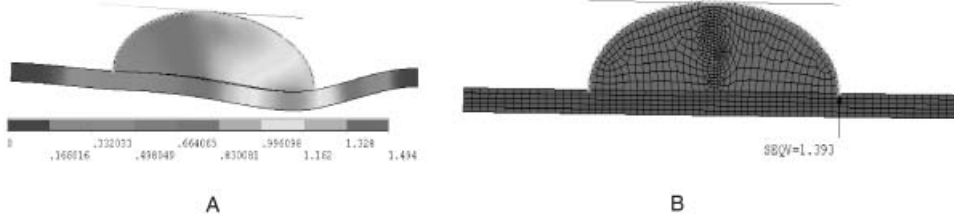


Fig. 7. (A) The displacement of blister and (B) the stress of hot spot. To account for stiffness effect of the contacting materials, the elastic modulus from 80 to 120 MPa of the worn outer the skin are compared for blister deformation and stress.

point of the blister simultaneously. Then, a sweeping frequency harmonic analysis as Eq. (3) was conducted to investigate the blister deformation at different frequency values.

$$[K][\phi] - [\lambda][M][\phi] = [F] \quad (3)$$

where the forces are modulated by multiplying with a harmonic term $\sin(\omega t)$ with ω as the angular frequency and t the time, i.e., $F_i = A \sin(\omega t)$ with A as the force amplitude.

The displacement amplitudes of blister at 1.6 and 6 Hz are extracted and compared as shown in Fig. 3. The displacement amplitude at 6 Hz is 15-fold as great as that at 1.6 Hz. This suggests that the displacement amplitude of blister is non-linearly proportional to the loading frequency before the resonance frequency. That is, even though the same forces are loaded on the skin, the fast runner is more susceptible to blister formation than a normal walker. In spite of this seemingly simple fact, no existing experiments or theoretical analysis have demonstrated this.

Next, as blistering results from the friction interactions between the skin and contact materials, the frictional coefficient contributes to a large degree to the process. Because of the blister symmetry about the related axis, a 2-D finite element model was used here to examine the effects. We consider the deformation and the Von Mises stress (29) at one hot point at interaction

$$\sigma_e = [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/2}$$

or

$$\sigma_e = [(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\sigma_{xy}^2 + \sigma_{yz}^2 + \sigma_{xz}^2)]^{1/2} \quad (4)$$

where σ_i is the i th principal stress, σ_j are stresses at $j = x, y, z$ axes, respectively, and $\sigma_{xy}, \sigma_{yz}, \sigma_{xz}$ are the corresponding shear stresses.

The effects of the frictional coefficient are calculated (Fig. 5), where four levels of the frictional coefficient from 0.0 to 0.4 are represented by figures A–E, and at each level, e.g., A1 shows

the blister displacement, and A2 represents the Von Mises stress. The results are summarized in Table 2.

From the figures and table, it is clear that the influence of the frictional coefficient μ is not monotonic. In Table 2, both stress τ_m and normal force P_n reach their corresponding maximum values at $\mu = 0.1$. As the range of μ in our study, 0.0–0.4, covers a wide range, our conclusion seems valid in general, except perhaps in the cases where the μ value becomes excessive.

The contact materials' stiffness is also a concern in blister forming and break. From our simulations, some interesting results are obtained. When the elastic modulus of contact material increased from 80 to 100 MPa, and then to 120 MPa under the same loads and friction coefficient, the tangential friction stress and normal pressure, displacement almost presented no change (as shown in Fig. 6). The result is somewhat different from the experiment (17) where different materials show different blistering scenarios. However, from our simulations, the elastic modulus shows no pronounced difference under the calculated range. With a complicated blistering-forming process, in the above experiments, the different blister events with contact materials may arise from the material moisture's difference.

Summary

Owing to the experimental difficulties and skin variations, we designed a non-linear dynamic finite element model to simulate the blister's deformation and stress under various loading conditions. From the mode and harmonic analysis, it is concluded that as our gait frequencies (both walking and running) are far below the lowest natural frequency of a blister, human activities are unlikely to lead to a resonance of blister, presumably with consequences such as broken blisters. Our analysis also indicates that

increased frequency will lead to monotonically increasing deformation and stress of the blister. It is, however, not the case for the friction coefficient that increasing the friction coefficient does not necessarily cause greater stress or displacement of a blister hot spot. In fact, there is a local maximum friction stress and Von Mises stress at certain friction coefficient values. Furthermore, the change of elastic modulus in contact material (within 20–30% range) has not generated significant effects on both the deformation and Von Mises stress. The model and method provided here demonstrated their robustness in evaluating material properties to prevent blistering. As an on-going project, we will use different fabrics with variable periodic tension forces on the skin to investigate the influences and also to further verify our model. Taken together, we do not wish to generalize the value of the model. At a minimum, it should provide a hypothesis validity, validated on decreased result for a common problem that decreases prevention efforts.

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