Original Article

The Influence of Effective Factors on Mechanical Stress on Fingertips during Snap-fit Assembly

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Objectives: Nowadays, Snap-fits are used in the automotive industry as a proper alternative for mechanical joints, cabling joints, and car interior lining joints. Due to the special form of these joints, which are assembled manually, the contact area between Snap-fits and the worker's fingertips can be too small. This can cause skin pain on the worker's fingertips. Therefore, an ergonomic study of these assembly operations can be useful for the automotive industries. This study was thus undertaken to investigate the severity of mechanical stress on fingertips.

Methods: In the first stage, the FEM-Method is used to analyse the influence of some effective factors including gender, age, the thickness of the epidermis of a skilled worker, wearing gloves, amount of force, force angle, and snap-fit material parameters during snap-fit assembly. For this purpose, four thumb models, 50% male and 50% female from 20-29 and from 50-59 years old, are used.

Results: The mechanical stress is directly associated with gender, age, thickness of epidermis, and the amount of force, and inversely associated with wearing gloves, and force angle.

Discussion: The maximum compressive stress and the greater deformation of skin in the male group as compared to the female group is due to the smaller size of women's thumbs and a less thick outer layer of women's skin. Moreover, for old people, a higher elastic modulus leads to a greater stiffness of their skin. Finally, the young people's modulus does not have a significant effect on the maximum compressive stress and total deformation of the skin.

Keywords: Assembly, Thumb, Snap-fit, mechanical stress, FEM

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Introduction

The application of Snap-fits in the automotive industry, in particular during assembly, as an appropriate replacement for bolts or other mechanical joints is rapidly increasing. The main advantage of using Snap-fits in assembly is saving assembly time because of the simplification and compression of assembly operations. Other advantages of these joints include insulation (electrical and thermal), lightweight material, and integration capability. The usage of these joints is not limited to linking two parts together. Rather, they can be used as conductors for cabling, piping and making car upholstery. Also, due to their integration capability, the possibility of the direct assembly of internal and external automobile parts is made possible using these snap-fits. Figure (1) shows some examples of these types of joints that are used in automotive industry.

Fig 1. Different samples of Snap-fits used in the automotive industry

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Although work with snap-fits can cause extremely high strains on the workers' skin and joints, there are few investigations into snap-fits' effects on skin, wrist joints, tendons, etc. Initially, Salmanzadeh [1] and Landau [2] studied possible ergonomic problems on the joints of workers who have to perform several thousand snap-fit motions per shift. Moreover, some experiments were completed by Landau [3] to examine the stress on the hand and forearm muscles of workers in the setting of snap-fit connections. In order to explain the productivity improvement with snap-fit systems, Landau et al. [4] concentrated on the effects of the snap-fit design in terms of operating time requirements for performing placement operations under mass assembly conditions. Another study, by Salmanzadeh et al. [5-6], studied the influence of snap-fits' sharp edges and total force on assembly time and muscular stress during assembly. Later, Salmanzadeh et al. [7] considered the ergonomic aspects of snap-fits and investigated the influence of different conditions such as the grasp and contact characteristics of snap fasteners on assembly time. Recently, an examination by Salmanzadeh [8] analysed the effects of gender on mechanical stresses on fingertips during snap-fit assembly, by designing some laboratory experiments. To the best of the author's knowledge, this study is the first time that a comprehensive study of the effective factors on mechanical stress and fingertip deformation is undertaken, using the Finite Elements Method (FEM) method. This research is the continuation of that article previously published by Salmanzadeh [8].

To study the deformation of fingertips while working with objects, some practical, analytical, and numerical methods are used in published papers. Numerical methods are mostly related to FEM. The results of studies in this field show that in the majority of studies, the intensity of the electrical potential on the skin's mechanical stress during contact with objects is related to tactile perception. When an object is in contact with the fingertip, skin touch receptors react [9]. With respect to the changes in the skin's form, electrical impulses generated by the receptors are sent to the brain by the nervous system [10]. These receptors are divided into 4 groups, based on the type of skin deformation that is caused by contact with objects. Merkel's discs are sensitive to static deformations, such as changes in form, shape, and size of objects. Ruffini endings are sensitive to skin stretching motions, like the displacement of a control button. Meissner's corpuscles and Pacinian corpuscles also react to the skin's dynamic motions and vibrations [11]. Impulses generated in receptors are directly proportional to the amount of skin deformation (mainly non-linear). The types and amount of various skin changes transfer different data about the shape, size, and contexture of the object to the brain, which are translated to neural signals [12-13]. Research in this field is performed with single-layer homogenous models and multilayer heterogeneous models. In the case of single-layer homogeneous models, analytical methods have also been used. Analytical models have been used to study the dynamic pressure of fingertips, and are based on viscoelastic equations [14-15]. These models have been also used for predicting fingertip deformation under static pressure [16-17]. However, these models cannot provide any estimation about stresses resulting from skin deformation. Unlike analytical methods, numerical methods such as FEM can investigate the distribution of skin stress and strain, and its correlation with receptor reaction, based on the computation of mechanically interconnected environmental models [18-19]. However, by considering the fact that single-layer models are far from the reality of fingertip anatomy, the consequences of these investigations are also different from reality. The first multilayer models in which the behaviour of each skin layer is assumed to be linear elastic were performed by Dandekar, [20] who used a three-dimensional model. Also, a two-dimensional model was designed and used by Gerling and Thomas [21]. In these models, with respect to the both micro-structure of skin layers and the mechanical properties of the different layers, an attempt has been made to provide models that are closer to reality. Of course, in some studies like [22] and [23], it was emphasized that the skin tissues are mostly nonlinear viscoelastic. Several studies by Wu et al. [24-25] used nonlinear models in order to analyse and evaluate the static and dynamic behaviour of finger skin while working with objects. In all the above-mentioned research, the behaviour of the sense of touch (reaction of receptors) was investigated, and the maximum force that was used in simulations did not exceed 5N; relatively greater forces are required during assembling Snap-fits. Thus, these models do not have enough endurance to implement the required simulations for examining the maximum tension and its relation with pain. Therefore, it is necessary to design a model which can examine the mechanical behaviour of the different layers (including skin deformation and internal tensions) while working with snap-fits. This paper attempts to examine the effect of some influential factors, including gender, age, and thickness of the epidermis for skilled workers, wearing gloves, the amount of force, the force angle, the material parameters of the clips, and the sharpness of the snap-fits on the model. The rest of the paper is organized in a way such that the proposed numerical method and software used to develop the geometric model are explained as the proposed method. The results of simulations and related discussions are then presented.

Methods

As mentioned in the introduction, examining the mechanical tensions that occur during snap-fits assembly on fingertips needs a steadier model than those proposed in the literature. Moreover, in order to make the simulation results closer to reality, an actual geometric model should be used. For this purpose, a CT scan of a real hand is chosen, with its bones and skin segmented by image processing techniques and AMIRA software. The related data is saved in standard STEP format, and then the three-dimensional geometric model is created with CATIA software. Figure (2) shows the aforementioned stages.

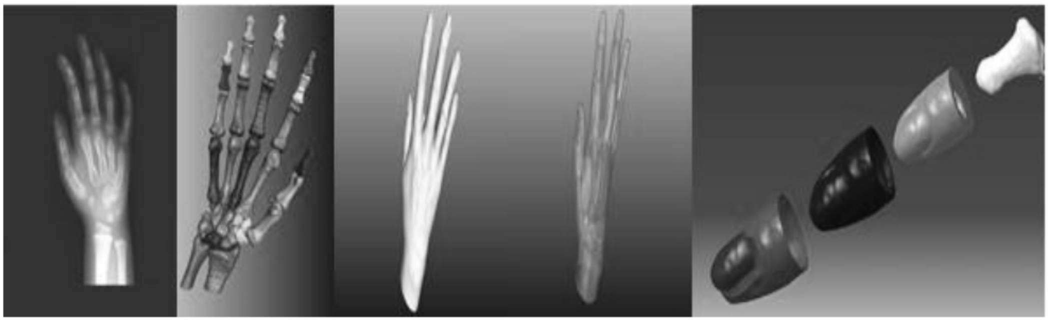


Fig 2. Steps of three-dimensional modelling of finger from CT scan to Segmentation and creating the model with CATIA

The three-dimensional model which is acquired after segmentation does not show the thickness of the various layers of the skin. However, in order to make the model closer to reality, using a multilayer model is necessary. Because the pain receptors are located in the middle layer of the skin (dermis), it is necessary to examine the correlation between stress and pain by calculating the maximum stresses in this layer. The amount of internal stress and its severity can be a sign of increasing pain. The position of receptors in several layers of skin is shown in Figure (3).

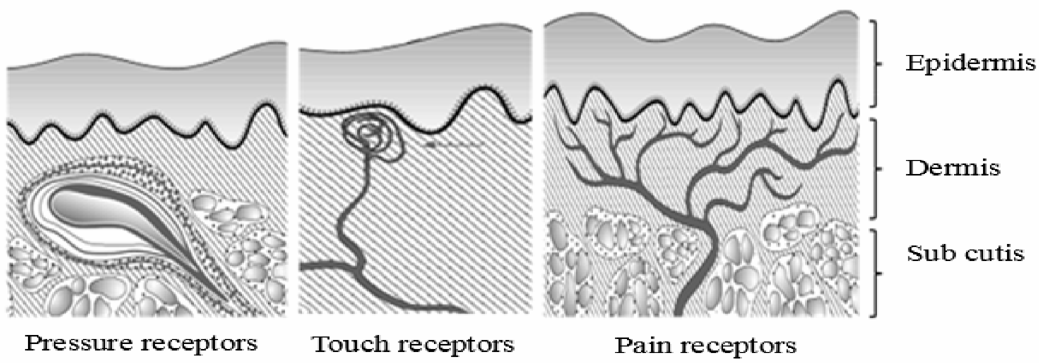


Fig 3. Position of skin receptors in different layers [26]

Also, with respect to Figure (4), which is taken from [27], it is obvious that at the fingertip, the lower skin is directly connected to the bone. The structure of the fingertip differs from other parts of the body, based on the fact that on the back of finger, the nail plate and the nail matrix are connected to the dermis [27].

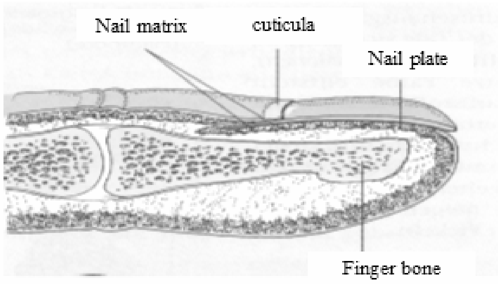


Fig 4. Structure of fingertip [27]

On the other hand, different skin layers with different thicknesses have different elasticity properties. So, in the next step, the model is developed to the three-layer (epidermis, dermis, and fat layer) model. For this purpose and to consider the thickness of different layers, the data as represented in [28] is used. This data is shown in table (1).

Table 1. the thickness of the various layer of skin on the thumb (μm)

All sizes in microns		Men	Women
Epidermis		450	360
Dermis	Age group (20 – 29)	2285	1803
	Age group (50 – 59)	1461	1519
Subcutaneous		The thickness of this layer depends on the size of finger	

In the next step of the model, four models for finger size (50% thumb models of males and 50% thumb models of females, from 20-29 and from 50-59 years old) are obtained by means of scaling the model with CATIA software in accordance with the standard data [29]. The 50% thumb model of males from 50-59 years old is designated as the reference model, because the experiments were done on this group in the laboratory, while for other groups the data are simulated based on the reference model. These data form the basis of the ANSYS software calculation in the next step. Then, the required network, boundary condition, and applied force of 5N and 50N are applied for each model with ANSYS software individually. Furthermore, the elastic properties of each layer of the skin and thumb bones is entered in the software for both models according to data [30] and [31] which are shown in table (2).

Table 2. The elastic modulus of bone and several layers of skin on the thumb (MPa)

Elastic modulus (MPa)	Age group (20 – 29)	Age group (50 – 59)
Epidermis	6	12
Dermis	0.6	1
Subcutaneous	0.15	0.25
Bone	17000	17000

Furthermore, it was necessary to consider the geometric shape of the snap-fit, its contact surface, and the motion's degree of freedom during force application in separate simulations for two models in order to determine the boundary condition. Figure (5) shows this process for the model of a male finger.

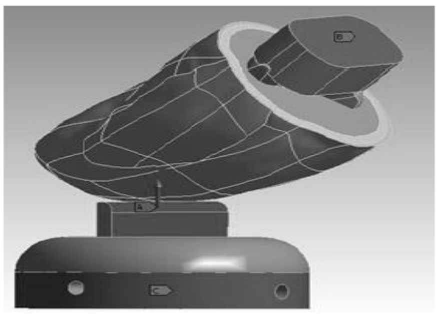


Fig 5. Determining the boundary condition

It should be noted that to achieve accurate and quick calculation, model networking was done in smaller grids in border areas-in particular at the contact points between the outer skin (epidermis) and the snap-fit's sharp edge. This gridline is shown in Figure (6).

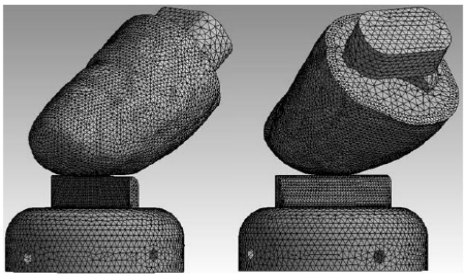


Fig 6. Networking of snap-fit and thumb model

To limit the rotation of the snap-fit, the snap-fit's rotational motion around its axis was fixed. Moreover, to avoid uncontrolled movements and to achieve the desired accuracy in calculations, the bones of the thumb joint were fixed, so they were only allowed to move along the longitudinal axis of the snap-fit.

Results

In this study, because of the location of the receptors, especially pain receptors, in the middle layer of skin, examining the maximum mechanical stress in the dermis is seen as more important. Also, the maximum amount of deformation in all the skin has been used as a criterion to evaluate the parameters. When force is applied (by pressing a finger on the snap-fit), maximum shear and maximum vertical stress do not always come into existence simultaneously at a certain place. For each volume element, apart from the finger skin's volume, an axis can be found by rotating that element so that the shear stresses are zero and the vertical stresses are maximum in that axis and vice versa [32]. Figure (7) shows the aforementioned volume elements.

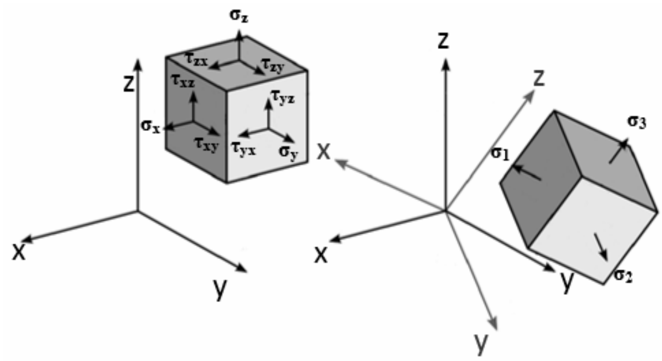


Fig 7. normal, shear, and primary stresses

With respect to Figure (7), it can be seen that the total deformation of the skin is determined by equation (1), when ux, uy, and uz represent the deformation of the skin in the X, Y, and Z directions respectively.

$$U_{total}\sqrt{u_x^z+u_y^z+u_z^z} \quad (1)$$

This maximum stresses which are mentioned as primary are compressive or tensile stresses. This means that, in this paper, since the process of pressing a finger on the surface of the snap-fit is investigated, the maximum calculated number will be found among the compressive stresses. The simulation results for age and gender (with reference models being males and females from 20 to 29 years old (young group) and from 50 to 59 years old (old group), based on a 50 N force) are shown in Table (3) for 5%, 50%, and 95% percentiles.

Table 3. The maximum compressive stress in the middle layer of skin (MPa) and the total skin deformation rate (mm) of 50N force for reference models

Gender	Male						Female					
Age	From 20 to 29 (young group)			From 50 to 59 (old group)			From 20 to 29 (young group)			From 50 to 59 (old group)		
Percentile	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%
Maximum compressive stress in dermis (MPa)	0.79	0.78	0.72	0.87	0.85	0.82	0.82	0.81	0.78	0.88	0.86	0.85
Deformation of the three skin layers (mm)	8.0	7.9	7.0	7.9	7.7	7.5	8.2	8.0	7.7	7.9	7.7	7.6

Comparing the results shows that the maximum compressive stress and the maximum deformation of the skin in the 50% young female group compared with the 50% young male group are greater, by about 3.7 percent and 1.2 percent respectively. Also, this difference is about 1.2 percent and 1.3 percent for the maximum compressive stress and the total deformation of the skin between the 50% old male group and the 50% old female group. For other percentile models, there are almost the same ratios.

To investigate the influence of the thickness of the epidermis for skilled workers, which can be caused by long-lasting stresses (for example by assembly work), based on the 50% old male group and by applying 5 N and 50 N force, the simulation results are presented in table (4).

Table 4. Comparing the results of simulation for the reference model and the model with thick epidermis

Model	50% old males (reference model)		50% old male with thicker epidermis (occupational model)	
Force	5	50	5	50
Maximum compressive stress in dermis (MPa)	0.21	0.85	0.14	0.46
Deformation of the three skin layers (mm)	1.3	7.7	0.8	3.2

With respect to the results, it can be seen that the maximum compressive stress and the maximum deformation of the skin for the reference model is greater than the occupational model by about 33.3 percent and 38.4 percent when the amount of force is equal to 5N, and by about 45.9 percent and 58.4 percent when the amount of force is equal to 50N, respectively.

As another result, to examine the influences of wearing gloves during snap-fit assembly, a simulation is performed for the 50% old male group with 2 mm supplementing gloves when 5N and 50 N force is applied (table 5).

Table 5. Comparing the results of simulation for the reference model and the model with gloves

Model	50% old males (reference model)		50% old male with gloves			
Force	5	50	5		50	
Young's modulus of gloves	Not relevant		250	500	250	500
Maximum compressive stress in dermis (MPa)	0.21	0.85	0.07	0.05	0.18	0.17
Deformation of the three skin layers (mm)	1.3	7.7	1.1	0.9	4.1	3.9

Table (5) illustrates a significant reduction in the maximum compressive stress and the deformation of the skin whilst wearing gloves. Also, the difference between the results with various values of Young's modulus can be seen in Table 5, as the maximum compressive stress and the deformation of the skin in the professional model with 250 young's modulus and 50 N force is less than the same measures in the reference model by about 78.8 percent and 46.7 percent respectively. These decreasing ratios are about 80 percent and 49.3 percent if a Young's modulus of 500 is considered. These differences confirm that gloves can decrease the pressure effects.

In continuing to present results, examining the effects of the amount of force may be of interest, hence the results of the simulations with different pressure forces are shown in table (6). As expected, the maximum compressive stress and the total deformation of the skin is increased by enhanced compressive force.

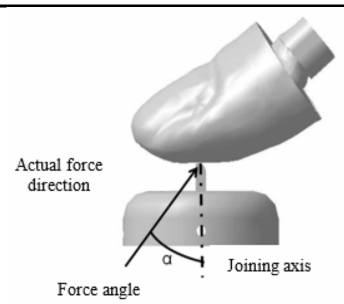
Table 6. Results of simulations with respect to the model with various force amount

Force	5	10	20	30	40	50	60	70
Maximum compressive stress in dermis (MPa)	0.21	0.36	0.45	0.56	0.69	0.85	0.88	1.36
Deformation of the three skin layers (mm)	1.3	2.3	3.8	5.3	6.5	7.7	10.4	13.9

In the previous simulations, it was assumed that the force was applied in the direction of the thumb axis, but in practice, this is not always the case. Also, depending on the spatial relationships, the force angle could be varied. Hence, to investigate the influence of the force angle on the maximum compressive stress in the dermis and deformation of the skin, corresponding simulations were performed with the reference model. It was simulated with a compressive force of 50 N, various force angles and the same clip material which is often used. The results of these simulations are shown in Table (7). These results mean that at a steeper force angle, the maximum compressive stress and the total deformation of the skin decrease.

Table 7. Results of simulations with respect to the model with various force angle

Actual force	Force angle	Maximum compressive stress in dermis (MPa)	Deformation of the three skin layers (mm)
50	0o	0.85	7.7
43.3	30o	0.78	6.9
35.3	45o	0.62	5.9
25	60o	0.54	4.6



In the last simulation, the influence of the material parameters of snap-fits on the maximum stress and skin deformation are investigated. Clips are made of different kind of plastics which have different stiffness and surface-textures. Thus, their influences are shown in table (8).

Table 8. Results of simulations with respect to the model with various snap-fit materials

E-module of clips (MPa)	500	1500	2000	3000	200000
Maximum compressive stress in dermis (MPa)	0.75	0.83	0.85	0.85	0.87
Deformation of the three skin layers (mm)	7.5	7.7	7.7	7.7	7.7

The results show that when the rigidity of clips increase, the deformation of the skin does not change and the maximum compressive stress increase only slightly, so that this should be interpreted as a numerical error.

Discussion

The results show that the aforementioned factors have effects on the maximum compressive stress in the dermis and on the deformation of the skin layers. Some factors have a positive influence and some of them react in an opposite way. By considering the results from Table 3, it is obvious that the maximum compressive stress and the total deformation of skin is higher in the male group than the female one. This is primarily due to the smaller size of the women's thumb in the selected age groups, which is about 14 percent smaller in comparison with the men's thumb size in the same age groups. Secondly, according to Table (3), the thickness of the outer layer of women's skin that (which acts as a protective layer) is 20 percent thinner than men's. For better comparison, the simulation results are shown in Figure (8) as a network chart.

Fig 8. Maximum compressive stress (left) and the total deformation of skin (right) for different thumb models

The left chart in Figure (8) shows that the maximum compressive stresses in the dermis decreases with increasing thumb size. According to the right chart in Figure (8), the same result applies analogously to the total deformation of skin. It can be seen that the total deformation of the skin has its lowest value at the 95% model. This can be explained by the fact that a larger thumb has thicker skin, so the fingertip is better protected from mechanical stress compared with smaller thumbs with thinner skin. Furthermore, based on the age comparison in Figure (8), an increase in the maximum compressive stress for old males and females is recognizable. This difference is reversed in the total deformation of skin. Thus, it can be seen that old people have a significantly higher elastic modulus, because old people's skin loses moisture by aging, leading to a greater stiffness of the skin [33].

According to table (4), it is possible that the smaller force, especially in people who have much experience in assembly work, would not be felt because of the thicker layer of their skin. Moreover, in table (5), the differences between the results of the various values of Young's modulus are recognizable. It should be noted that the maximum compressive stress and the total deformation of the skin only increases about 10 percent when the Young's modulus is doubled. Thus it can be concluded that a change in Young's modulus does not have a significant effect on the maximum compressive stress and total deformation of the skin. Furthermore, in the results of the simulations for various force amounts, a linear correlation between the maximum compressive stress and the total deformation of skin was observed with a high correlation coefficient (about 0.985). This correlation is shown in Figure (9).

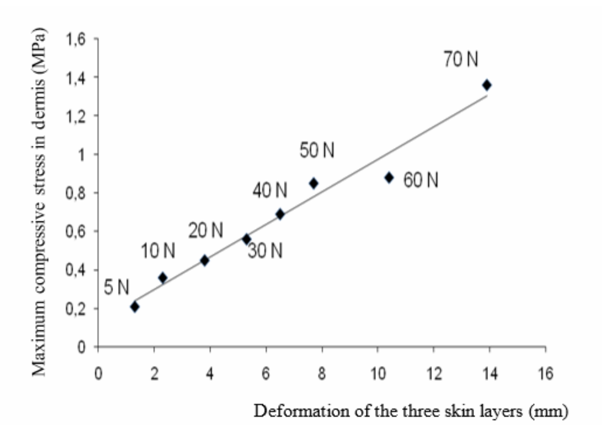


Fig 9. Correlation between the maximum compressive stress in the dermis and the total deformation of skin

In table (7), the actual force is derived from the force multiplication with the cosine of the force angle. For example, when a 50 N force is required, the pressure force at the steeper angle should be increased accordingly. The influence of the elevated compressive force can be examined in more detail through further simulations in the future. In addition, simulations for various snap-fit materials indicate that only a material with an E-module of 500 MPa led to lower measures in comparison with other tested modules. This explains the fact that the compressive stress and the deformation of skin decrease in soft materials. Also, the variation of the friction coefficient as a property of the surface-texture has no significant influence on the maximum compressive stress and the total deformation of the skin. This is due to the fact that all simulations were carried out with a positive contact. For power transmission in friction-stressed condition, an influence of the surface texture is expected, which can be examined in future studies.

Finally, because the computation only provides answers after a relatively long time, and only with frequent adjustment of ANSYS software, in this paper only calculations and simulations related to the four aforementioned models have been performed and compared. Therefore, some complementary experiments aimed to examine further groups for developing more accurate models can be a worthwhile field of research. Furthermore, examining the influences of effective factors by means of implementing some real experiments in laboratories can obtain more accurate and precise results. Thus further investigation of these factors using real experiments on some groups of males and females is another research topic which is recommended by the authors.

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