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Numerical Simulation of Dynamic Pressure and Displacement for the Top Part of Men's Socks Using the Finite Element Method

Abstract

Numerical simulation of elastic human body deformation and dynamic pressure and displacement distribution are critical for pressure comfort and optimal design of apparel products. This paper demonstrates an analytical method for simulating dynamic pressure and displacement at the top part of men's socks using the finite element method (FEM). The dynamic pressure is divided into two parts: the first is pressure with time, and the second is pressure with walking. Pressure with time is set at six periods (maximum 12 h). After measuring pressure values in different periods of time and simulating pressure and displacement distribution using ANSYS software, the tendency of pressure and displacement changes with time at the top part of men's socks can be obtained. We divided the walking process into four phases to analyse the variation rule of pressure and displacement changes with movement in this research work. Meanwhile the lower leg cross section is divided into four equal regions according to the angle, and dynamic changes in the area shrinkage mass of each region can be calculated, respectively. All these solutions provide a theoretical reference for the optimal design of the top part of men's socks.

Key words: top part of socks, pressure, displacement, finite element, dynamic.

Introduction

Recently, with the rapid development of demands on the quality of clothing production, the performance of garments has become more and more important. Modern consumers demand clothing products with superior multi-functional and comfort performance to meet their physiological and psychological requirements. Clothing comfort such as pressure comfort has been identified as one of the most important attributes [1]. Mechanical interaction between the human body and top part of socks is an important factor affecting wearing comfort [2]. In the authors' previous article [3], a simulation model of the lower leg cross section located at the top part of men's socks was presented through three-dimensional body scanning. A numerical simulation of the pressure and displacement was done using ANSYS10.0 software. In document [3], the human body was regarded as an elastomer and contact between the lower leg and top part of men's socks was considered to be an elastic contact. In the middle of the test, subjects wore experimental socks (A1, A2, A3, B1, B2, B3) in a sitting position. The position was

described as sitting upright on a flat seat and with a flat back rest, the chair being 45cm from the floor. Pressure values between the top part of socks and the lower leg cross section were instantaneous and static datum. Finally we obtained the pressure-displacement quadratic equation through curve fitting. These solutions provided a theoretical reference for the optimal design of the top part of men's socks.

However, it is impossible for the human body to maintain a state of rest when wearing socks in practical life as most of the time it is in motion. Moreover the contact pressure and corresponding displacement values would also change with time. In recent years, some scholars have pointed out that the pressure variation between the human body and garment in the whole walking cycle is an important issue in research and development work [4 - 6]. Obviously it is more meaningful to thoroughly study the dynamic pressure and displacement distribution for the top part of men's socks than static and instantaneous factors in order to ensure pressure comfort. Nevertheless little research on dynamic pressure for the top part of men's socks has been reported. Toshiyuki Tsujisaka [7] observed the relationship between pressure values and pressure feelings for the top part of men's socks through measuring the mean pressure values, obtained instantaneously and two hours after putting on the socks, respectively. The results showed that the wearing time influenced pressure feelings, which agrees with Nishimatsu's theories

[8]. Li Jing [9] illustrated the pressure changes with time (maximum 4 h) at the top part of socks, revealing that the pressure values gradually decreased with time and then reached a relatively steady state at 2 h after putting on the socks.

This article was an in-depth study and continuation of research based on document [3]. In this paper the subjects, sample socks and shape of the lower leg cross section located at the top part of the men's socks were all the same as in document [3]. In this paper, the dynamic pressure was divided into two parts: the first was pressure with time, and the second was pressure with movement. The pressure with time was set at six periods (maximum 12 h). After measuring pressure values in different periods of time and simulating the pressure and displacement distribution using ANSYS software, the tendency of pressure and displacement changes with time at the top part of men's socks could be obtained. For the movement state, we selected a walking pattern because walking is the most popular form of movement for the human body in normal circumstances under natural conditions [10]. In this research work, we divided the walking cycle into four phases according to the walking characteristic and analysed the variation rules of pressure and displacement changes at each stage, respectively. The study of dynamic pressure and displacement provided a more practical theoretical reference for the optimal design of the top part of men's socks.

■ Experimental

Basic diagram of the lower leg cross-section

The shape of the lower leg cross-section located at the top part of socks is an important factor affecting the pressure values directly. Most research published has focused on regarding the lower leg cross section as a circle. In fact, the real shape is of irregular geometry. Moreover, many researchers selected a standard round wooden test model of the lower leg with a circumference of 21 cm, according to documents [11 - 13]. However, the human leg, unlike wooden material, is a complicated elastic body [14]. In document [3], we selected 30 Chinese college students with a standard shape and aged 20 to 25 as subjects, and then established a model of the lower leg cross-section located at the top part of a man's sock through three-dimensional (3D) body scanning based on ergonomics. The 30 lower leg cross-section curve images were stored and each 5 degree interval was segmented in a plane rectangular coordinate system. Using MATLAB 7.0 software, a 72-point coordinate value was determined, average x and y values of the 72 points coordinate, and an average shape of the cross-section were obtained (units: mm) (*Figure 1*) [3].

Pressure experiment

The samples used in document [3] consisted of six men's socks on the market, which were divided into two groups: Group 1 (A1, A2, A3) were socks whose main constituent was nylon, and Group 2 (B1, B2, B3) were cotton. To minimise the instability of the knitted fabric, all sample socks were conditioned in a standard environment for 24 hours (temperature 21 ± 1 °C, relative humidity $65 \pm 2\%$, according to the American Society for Testing and Materials D1776-04), and we assumed that the fabric was evenly stretched in each part.

30 healthy males, as mentioned in document [3], participated in the study. This experiment was carried out in an environment-controlled chamber with a temperature 21 ± 1 °C and $65 \pm 2\%$ relative humidity. In the middle of the experiment, we needed to measure dynamic pressure values, which were divided into two parts: The first was pressure with time, and the second was pressure with walking. Subjects were required to wear six sample socks for different periods of time and postures according to the experiment

scheme, and then the contact pressure at 72 points between the top part of the men's socks and the lower leg cross section were measured with a clothing pressure measurement device (AME3037S-5, Japan), the units being kPa. To eliminate interobserver variability, the same operator performed all measurements for all subjects.

■ Results and discussion

Pressure and displacement changes with time

Pressure changes with time

Generally, socks will not be continuously worn more than 12 hours a day in actual life. Pressure values will change with time at the top part of socks. We deeply discussed the pressure variation tendency with time and decided it could supply a theoretical reference for the optimal design of the top part of men's socks. Based on this, we defined the maximum time of wearing the sample socks as 12 hours in this paper, and divided the periods of time into six stages according to physiological characteristics of the human being, which were instantaneous, 1, 2, 4, 8 and 12 h, respectively.

In this research work, we selected six different time points to measure the pressure values at 72 points on the lower leg cross section using a clothing pressure measurement device - AME3037S-5, which are instantaneous pressures lasting 1, 2, 4, 8 and 12 h after putting on the six sample socks, respectively.

Swelling is generally the worst in the lower legs after walking, standing, or sitting in a chair for a period of time, or at the end of the day. Compression stockings or support stockings could provide support for the legs and keep blood and fluid from pooling in the legs, thus reducing swelling and leg fatigue [15]. In this study, the transient pressure was determined for different periods of time. Although swelling was generated in the lower leg as time lengthened, swelling because of sock pressure could be largely reduced on the lower leg located at the top part of men's socks. Based on this, the change in pressure on the lower leg cross section caused by swelling of the leg was negligible in this research work.

In this paper, we always took sample sock A1 as an example. The pressure values in different periods of time at 72 points are shown in *Figure 2*.

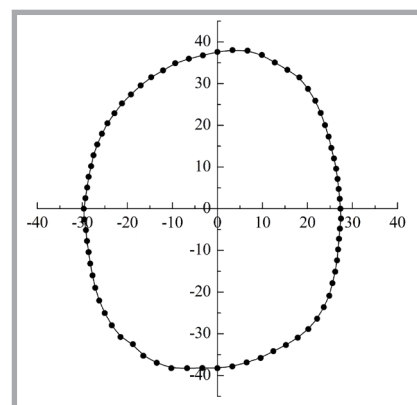


Figure 1. Shape of the lower leg cross section [3].

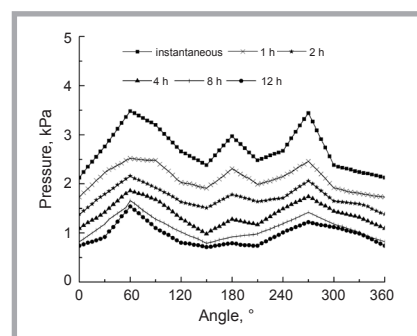


Figure 2. Pressure values in different periods of time.

Figure 2 shows the mean pressure values at 72 points in different periods of time. The horizontal axis represents the angle, and the vertical axis - the pressure values. The results suggested that all pressure values gradually decreased with time. Furthermore all the pressure curves presented basically the same change in the relationship in each period of time.

We can see from *Figure 2* that the highest pressure value was exerted at a 60° and 270° position, and the lowest at 0° in all six periods of time. When first putting on the sample socks, the instantaneous pressure value at 270° was 3.44 kPa, decreasing to 2.46 kPa after one hour, which was a drop of 28.49%. The instantaneous pressure value at 0° was 2.13 kPa, which then decreased to 1.73 kPa after one hour, representing a decline of 18.78%. It was obvious that at the location with the largest instantaneous pressure value, the greatest pressure value decrease would be within the first one hour. After 12 hours of wearing the sample socks, the pressure value at 270° dropped to 1.22 kPa, with the descent rate being 64.53%. The pressure at 0° was 0.74 kPa, which was a decrease of 65.26%. Results showed that the descent rate of the pressure value at each point of the top part of men's socks

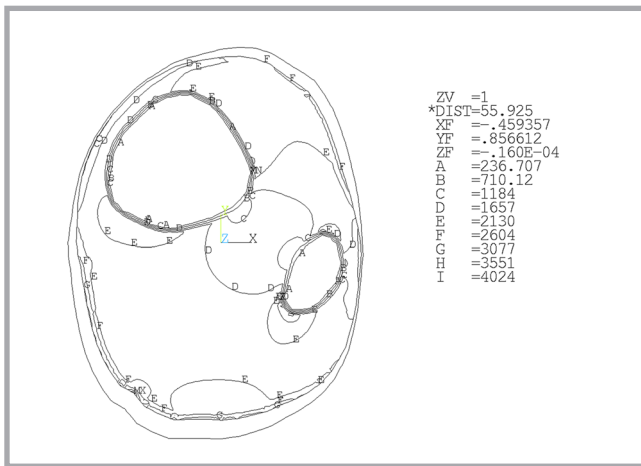


Figure 3. Stress contour map of the lower leg cross section after 1 h.

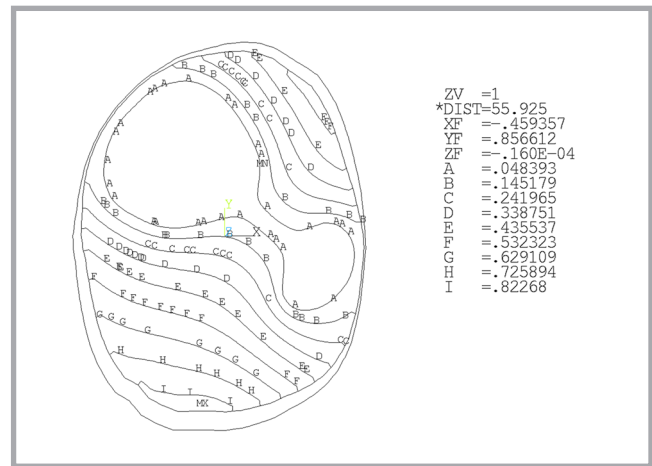


Figure 4. Displacement contour map of the lower leg cross section after 1 h.

tended towards a balanced condition as time passed after putting on the socks.

From **Figure 2**, we can clearly conclude the following: The pressure values gradually decreased with time. In the first 1 h, they decreased significantly, approximately one-third of the total rate of descent. After 2 h, it decreased by about a half of the total. Subsequently, the descent rate of the pressure values decreased less and less as time passed, dropped much less when wearing the socks for over 8 hours, and the values became basically the same at 8 and 12 h. It was concluded that the pressure values were almost stable after 8 h wearing the socks. The gap between the maximum value of pressure and the minimum at the same time became smaller and smaller gradually with time, and the values at 72 points tended to be basically the same in the end.

Stress and displacement simulation with ANSYS

When inputting the pressure values at 72 points into ANSYS 10.0 as pressure boundary loads, the method of meshing,

material properties and element types of the finite element model were all the same as in document [3]. In this article, we put the displacements of the tibia and fibula both equal to zero in the X, Y orientation as boundary conditions of the finite element model. After solving and post-processing, the stress and displacement contour map of the lower leg cross section could be calculated by ANSYS software. Here A1 is taken as an example, as shown in **Figures 3** and **4**.

Figures 3 and **4** show the stress and displacement contour map of the lower leg cross section after putting on sock A1 for 1h, respectively. The peripheral curve is the original shape of the cross-section of the lower leg before being under stress, and the inside curve is the deformed curve. Letters A, B, C, D, ... represent the distribution of stress and displacement, respectively. The regions of higher values are marked with the letter I, and those with lower values are marked with the letter A. **Figures 3** and **4** show directly the stress and displacement distribution of the lower leg cross section after having worn the sample socks for 1 h.

Displacement changes with time

Figure 5 illustrates the displacement distribution at 72 points in six periods of time.

It can be seen from **Figure 5** that the displacement values of the lower leg cross section increased with time, which was contrary to the tendency of changes in pressure. There was basically the same relationship of displacement distribution in the six periods of time. The highest displacement value occurred at 270°, and the lowest at 0° in all the six periods of

time. The displacement values significantly increased within the first 1 h after putting on sample sock A1, approximately one-third of the total rate of ascent. 4 hours after putting on the sock, it increased by about a half of the total, and then the ascent rate increased less and less as time passed. After 12 hours, the highest displacement value point (270°) increased from 1.178 mm to 4.44 mm i.e. by 3.77 times, the lowest point (0°) from 0.11 mm to 0.41 mm i.e. by 3.73 times, and the highest value was approximately double the lowest at the same period of time.

Area shrinkage mass of lower leg cross-section changes with time

In order to study the area shrinkage mass of the lower leg cross section after putting on the sample socks, in this research work, the original curve of the lower leg cross section and deformed curve under stress were all divided into 72 points according to angle. Four neighboring points formed an irregular quadrangle. Supposing the coordinate values of four neighboring points are $M_n(x_n, y_n)$, $M_{n+1}(x_{n+1}, y_{n+1})$, $M'_n(x'_n, y'_n)$, $M'_{n+1}(x'_{n+1}, y'_{n+1})$, respectively (**Figure 6**), the area of the quadrangle is S_n :

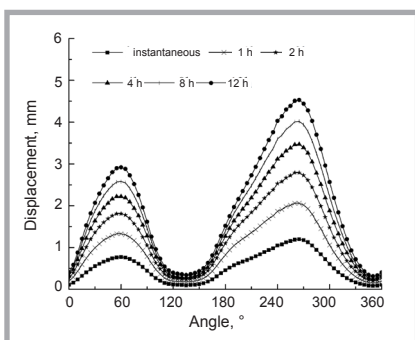


Figure 5. Displacement values in different periods of time.

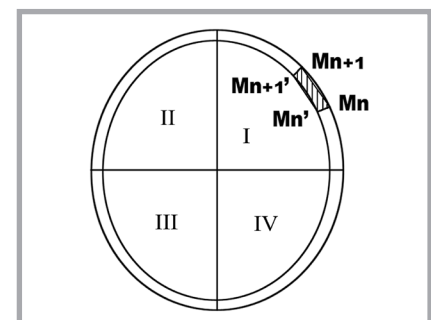


Figure 6. Area diagram [3].

$$S_n = \frac{1}{2} \left\{ \begin{aligned} & \left| \begin{matrix} x'_n & y'_n \\ x_n & y_n \end{matrix} \right| + \left| \begin{matrix} x_n & y_n \\ x_{n+1} & y_{n+1} \end{matrix} \right| + x_n y_n \\ & + \left| \begin{matrix} x_{n+1} & y_{n+1} \\ x'_n & y'_n \end{matrix} \right| + \left| \begin{matrix} x'_n & y'_n \\ x_{n+1} & y_{n+1} \end{matrix} \right| \end{aligned} \right\} \quad (1)$$

In this research work, the cross-section of the lower leg was divided into four equal regions, which were (0°, 90° – region I), (90°, 180° – region II), (180°, 270° – region III) and (270°, 360° – region IV) (Figure 6). Here we took A1, for instance, and then the total area shrinkage mass of the four regions in different periods of time could be calculated with equation (1), respectively (Figure 7).

It was found in Figure 7 that the total area shrinkage mass of four regions in different periods of time all showed an increasing tendency. In the six periods of time, (180°, 270° – region III) had the largest area shrinkage mass on the cross-section of the leg in the whole time; (90°, 180° – region II) had the smallest, and (0°, 90° – region I) and (270°, 360° – region IV) had roughly the same. Region III has approximately triple the area shrinkage mass of region II, and double that of regions I and IV when first putting on the sample socks. The variation in the area shrinkage mass was most evident in region III and least in region II with an increase in wearing time. After 12 h of wearing sock A1, the area shrinkage mass in region II increased by 3.45 times, and region III by 3.6 times. Since there is the tibia in region II and the soft tissue layer is thin, the displacement of the lower leg cross section would come into equilibrium after a period of time under stress. Consequently the increase in area shrinkage mass in region II is slightly less than that in other regions as time goes by. On the other hand, in region III, where the soft tissue layer is thick, it is evident that the displacement change is larger when other parameters are the same.

Pressure and displacement changes with walking

The pressure variations between the top part of socks and the lower leg cross section in walking is critical for the optimal design of the top part of socks. However, it was difficult to accurately record the whole course of pressure variations in walking using existing pressure instruments. The research of dynamic pressure testing between clothing and the human body remains in its infancy [16]. In order to make the investigation simple, we divided the walking process into several phases in this study.

Process of walking

Walking is a complicated process. At the end of the fifteenth century, Italian scientist Leonardo Da Vinci researched a variety of positions and movements for the human body, and first put forward an important opinion that all moving organisms follow the laws of mechanics [17]. The study of mechanics and kinematics in walking was started by Aristotle. He firstly described the effect of muscle in movement, and then analysed the complicated process in walking [18]. In recent years, a considerable amount of researches have been conducted to study the walking process for the human body. Bruderlin and Calvert divided the walking process into several stages and made a series of detailed analyses in 1989 [19]. Walking is a circular and periodic movement of the human body, with each stride consisting of two symmetrical steps during the course of walking. In this article, we assumed a walking cycle beginning at one side of heel contact and ending at the same side of heel contact again during the process of walking, and then the walking cycle could be divided into eight phases in normal circumstances (Figure 8).

In this research work, the right leg was regarded as the study object. One walking cycle could be divided into the stance

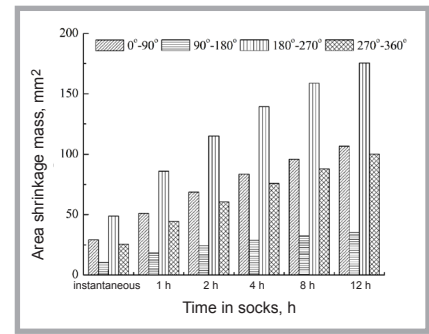


Figure 7. Changes in the area shrinkage mass of the lower leg cross section with time.

phase and swing phase. As seen in Figure 8, one step cycle in walking consisted of one double support process and one single support process. The normal walking cycle was described as follows:

$$\begin{cases} t_{step} = t_{swing} + t_{ds} \\ t_{step} = t_{stance} - t_{ds} \\ t_{cycle} = 2t_{step} \end{cases} \quad (2)$$

Where t stood for one stance phase. For the stance phase, the process included five links, namely, (a), (b), (c), (d) and (e) in Figure 8. These were described as heel contact, sole contact, stance metaphase, heel off the ground and toe off the ground, respectively [20]. The stance phase is the first step in the walking process in my research work. When the human being is in the stance metaphase step, there should be an average distribution of the weight on the two feet. The swing phase included (f), (g) and (h), being the swing early phase, swing metaphase and swing anaphase. The swing phase is the second step in the walking process. After accelerating from the swing early phase to the swing metaphase (g), the lower leg was in a vertical position, then decelerated to the swing anaphase (h), and finally terminated in heel contact (a). When the right leg stepped into the swing early phase (f), the calf swung forward rapidly and gradually decelerated when entering the

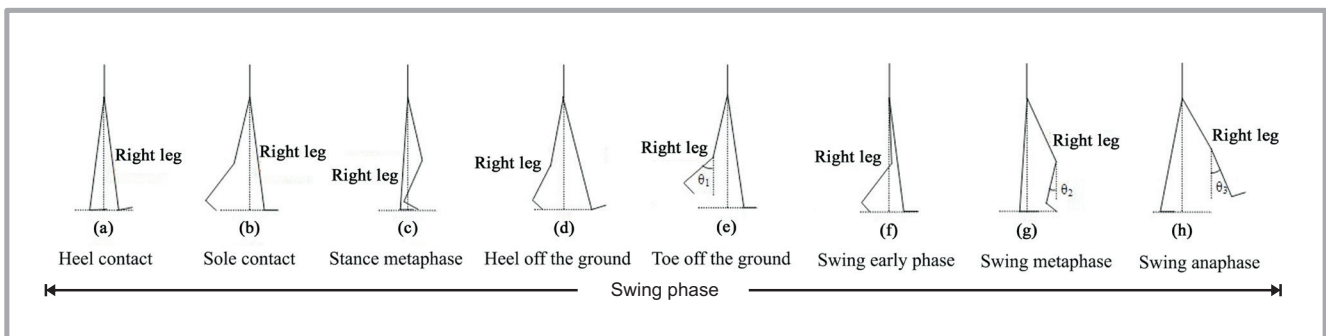


Figure 8. Walking cycle.

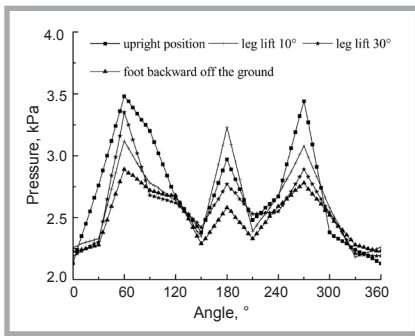


Figure 9. Pressure values with walking.

swing anaphase stage (h). In this step, the whole weight should be put on the left foot completely. The swing speed of the calf would decrease to zero until the swing process was over [21].

Pressure changes with walking

Walking belongs to the domain of kinematics. In kinematics, one analytical method is to put a sensor on the location of the joint, from which we can obtain the immediate and precise motion parameters in different parts of the body during the course of movement in each period of time. Zeltzer designed a hierarchical task-oriented system in 1982 providing a simulation of human walking based on the measurement datum in this system [22]. In this paper, we applied the same measurement approach to get pressure datum between the lower leg cross section and the top part of men's socks during the course of walking. We selected four important phases in one walking cycle. These were (c), (e), (g) and (h), as shown in Figure 8. In this experiment, the four phases were described in the upright position (c), foot backward off the ground (e), leg lift 10° (g), and leg lift 30° (h), respectively. The angle was de-

finied as that included between the right calf and vertical line.

Figure 9 shows the results of the pressure values at 72 points in the four phases.

Figure 9 depicts pressure variations in walking. The results showed that the pressure values presented basically the same change in relationship in the four phases during the course of walking. The pressure values increased to the maximum when the subjects were in an upright position (c). It was also found in Figure 9 that at lower pressure value positions, such as 0°, 150°, 210°, 330° etc, pressure exerted on the lower leg cross section changed little during the whole walking process, which was contrary to the larger pressure value positions, such as 60°, 180° and 270°, etc. On the whole, for most regions of the lower leg cross section, the pressure was higher when the subjects were in an upright position than in the other three phases, and the pressure values basically maintained a minimum all the time when the subjects were in the foot backward off the ground phase (e) because a different force was applied by the leg muscles in different phases during the course of walking, with the pressure changing correspondingly with the stretch and contraction of the muscles.

Stress and displacement simulation with ANSYS

Inputting the pressure values at 72 points into ANSYS as pressure boundary loads, after solving and post-processing, the stress and displacement contour map of the lower leg cross section could be calculated. Here we took A1 at the leg lift 10° (g) position as an example (Figures 10 and 11).

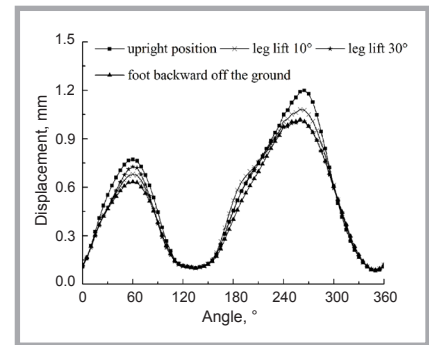


Figure 12. Displacement values with walking.

Figures 10 and 11 depict the stress and displacement contour map of the lower leg cross section at the leg lift 10° position when wearing sample sock A1.

Displacement changes with walking

Figure 12 illustrates the displacement distribution at 72 points in the four phases during the course of walking through ANSYS simulation.

It can be seen from Figure 12 that there was basically the same distribution relationship of displacement values in the four phases during the course of walking. Higher displacement values occurred at the 60° and 270° positions for the whole time in each phase, and the highest occurred when the subjects were in the upright position. The displacement did not change significantly with walking at lower displacement positions, such as 0°, 120°, 150° and 330° etc. The results showed that the displacement increased in the (0°, 60°), (135°, 270°) and (350°, 360°) regions, and decreased in the (60°, 135°) and (270°, 350°) regions during the course of walking.

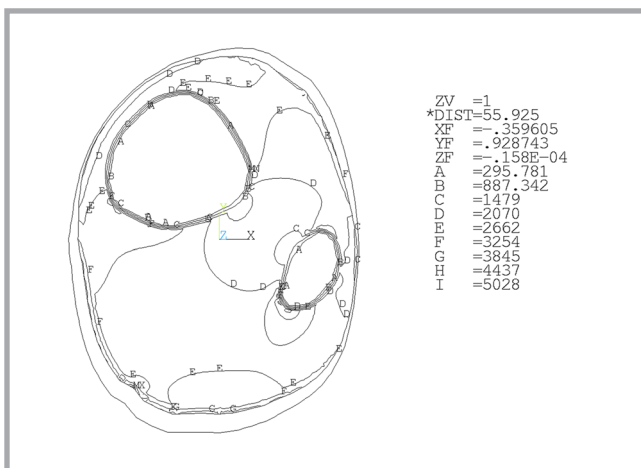


Figure 10. Stress contour map of the lower leg cross section at leg lift 10°.

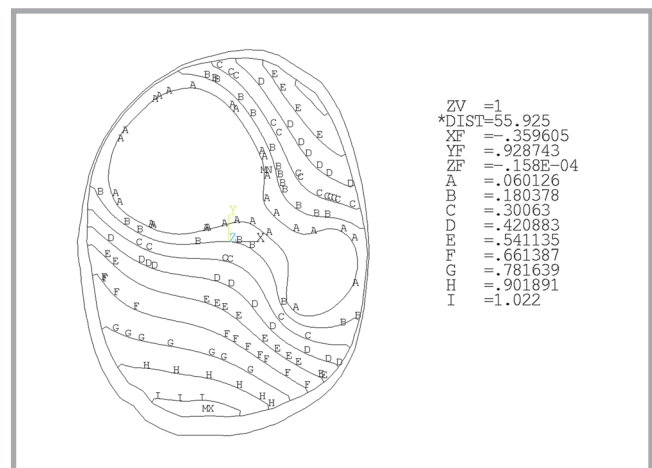


Figure 11. Displacement contour map of the lower leg cross section at leg lift 10°.

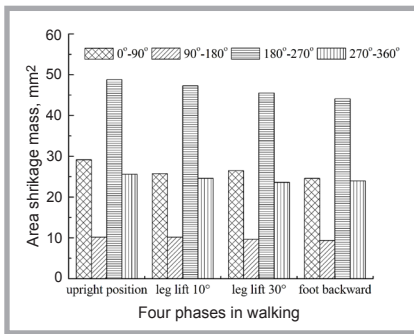


Figure 13. Area shrinkage mass of the leg cross section with walking.

Area shrinkage mass of lower leg cross-section changes with walking

The total area shrinkage mass of four regions in different phases during the course of walking could be calculated with equations (1), respectively. (Figure 13).

It was found in Figure 13 that the total area shrinkage mass of four regions changed little during the course of walking. Nevertheless it was slightly higher when the subjects were in an upright position than that in the other three phases. One direct and powerful explanation was that the leg was subjected to the highest counterforce from the ground when the human body was in an upright position, leading to muscle contraction, and then the pressure and displacement of the lower leg increased. In the four phases, (180°, 270° – region III) had the largest area shrinkage mass on the lower leg cross-section in the whole process; (90°, 180° – region II) had the smallest, (0°, 90° – region I), and (270°, 360° – region IV) had roughly the same. Region III has approximately triple the area shrinkage mass of region II, and double that of region I and IV when wearing the sample socks.

Conclusions

Dynamic garment pressure and displacement distribution is critical for the pressure comfort and optimal design of apparel products. In this study, we objectively measured the pressure between the lower leg cross section and the top part of socks. After simulation with ANSYS software, the corresponding displacement datum could be obtained. Tests show that the pressure values of the top part of socks gradually decreased with time. The pressure values significantly decreased within the first 1 h, and then the descent rate of pressure decreased

less and less as time progressed, finally reaching a basically stable situation 8 hours after putting on the socks. The gap between the maximum value of pressure and the minimum became smaller gradually, and the pressure values at 72 points tended to be basically the same in the end.

The displacement values of the lower leg cross section increased with time, significantly increasing within the first 1 h after putting on the sample socks by approximately one-third of the total rate of ascent. After 12 h, the highest displacement value increased by 3.73 times of its initial value. The total area shrinkage mass of the four regions in different periods of time all showed an increasing tendency. In the six periods of time, (180°, 270° – region III) had the largest area shrinkage mass on the cross-section of the leg during the whole time, increasing to 3.6 times as large as the initial value.

For most regions of the lower leg cross section, the pressure was highest when the subjects were in an upright position during the course of walking, and the minimum occurred at the foot backward off the ground stage. There was basically the same distribution relationship of displacement values for the four phases in walking. The highest pressure occurred when the subjects were in the upright position at the higher displacement value position, and the displacement did not change significantly with walking at lower displacement positions. The total area shrinkage mass of the four regions in different phases changed little during the course of walking. Nevertheless the total area shrinkage mass is slightly higher in the upright position than that in the other three phases. All these solutions provide a theoretical reference for the optimal design of the top part of men's socks.

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