Chapter 38
Friction Behaviour of Medical Compression Stockings Against Various Mechanical Skin Models

Wei Ke, Jiyong Hu and Xin Ding

Abstract To determine a promising skin model for exploring the friction behaviour of medical compression stockings (MCS), the dynamic friction properties of MCS against with two kinds of mechanical skin models are investigated in the current study. For further investigation, the difference on the friction of the two models are analysed in detail with adhesion friction model and Hertz contact theory. The coefficient of friction (COF) of MCS/Lorica is 0.34 ± 0.01, which is closer to the COF of human skin/MCS (0.36 ± 0.04), while the COF of MCS/PUR is 0.89 ± 0.01, with an increasing factor of 2.6, mainly due to the variation of elastic modulus. It can be concluded that Lorica has similar dry friction behaviour as the human skin, and elastic modulus could be the main reason to the difference on the friction of two models.

Keywords Skin-textile friction · Medical compression stockings · Hertz contact model · Adhesion friction mechanism

38.1 Introduction

Medical compression stockings (MCS) is a kind of medical textile products, which has been widely used in compression therapy for reliving symptoms associated with venous disorders in lower human limbs [1]. It can perfectly alleviate the related limb diseases because of the defined pressure exerted on the limb skin, as well as generate unavoidable friction simultaneously. It is generally acknowledged that the friction from the inappropriate size of MCS (e.g. too tight) contact with skin during long-time wearing will produce skin injuries such as pressure patterns, blisters or ulcers [2]. Thus, the friction behaviour of MCS in contact with the skin

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is an important factor. However, a lot of studies have just paid attention on the compression properties and therapeutic effect of MCS [3], with ignoring the friction properties of MCS contact with human skin.

To investigate the friction properties of textiles/skin and also avoid the uncontrolled factors from human skin, various objective devices using linear or rotational relative movements have been developed in the past [4]. Instead of using arbitrary materials such as steel [5] as the skin models in contact with textiles, the use of soft materials such as a polymer finger or a polyurethane (PUR) film [6] seems to be reasonable.

In previous study [7], in order to investigate the influence of surface topography on the friction of MCS, we have chosen PUR sheet as the candidate skin model to do the friction tests and theoretic work, for simplifying the contacts between MCS and human skin, but it is not entirely according to the realistic state. Then, Lorica, whose surface is similar to the forearm skin, was chosen as the skin model to exploring the friction properties of MCS in this study, and for comparison, a PUR sheet was used as a reference material throughout the study. For further investigation, Hertz contact model was used to explore the differences in detail.

38.2 Experimental

38.2.1 Materials

38.2.1.1 Investigated Textiles

A typical commercial knitted elastic textile of MCS (compression class 1, CcI1 for short) was selected in this study. The material is composing of 52 % polyamide, 34 % spandex and 14 % cotton. The optical microscopic image and its surface topography were given in Fig. 38.1.

It can be seen that the structure of MCS is quite different from the other traditional socks, it includes two components: the inlaid or covered yarns and the knitted loops. The inlaid yarn is a synthetic elastic yarn with textile filaments wrapped around it. This component is inserted between the loops, which constitute the base structure of the fabric and play a key role in forming the topography of stocking samples.

38.2.1.2 Mechanical Skin Models

Two kinds of materials which are widely used as the mechanical skin models were selected in the experiment. One is a structured artificial leather, named Lorica showed similar surface structure as human skin (See Fig. 38.2a, b) which consists of a polyamide fleece with a PUR coating. The other one is a relatively smooth sheet made of PUR (Fig. 38.2c). The specifications of the two skin models are given in Table 38.1.

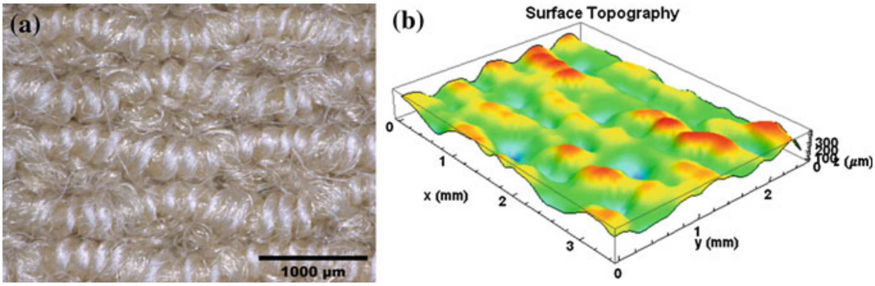

Fig. 38.1 The optical image of MCS (*right*) and its topography image (*left*)

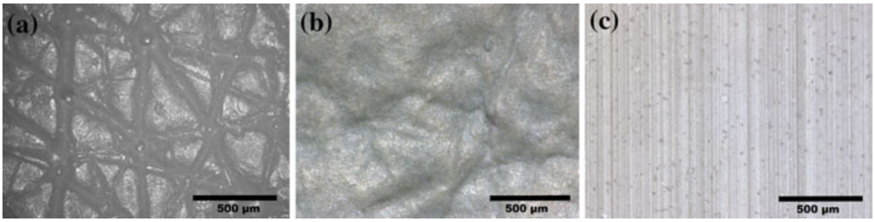

Fig. 38.2 The optical image of real forearm skin replica form the first author (**a**) and Lorica skin model (**b**) and PUR skin model (**c**)

Table 38.1 Characteristics of materials investigated as skin models [8]

Material	Thickness (mm)	Roughness Ra (µm)	Hardness shore A	Elastic modulus (MPa)
Lorica	0.9	14.93 ± 1.73	42.5 ± 1.8	24.4
PUR	1	0.21 ± 0.02	70.2 ± 0.4	10.8

38.2.2 Friction Measurements

A friction tester described in [9] was used to investigate the friction behaviour of textiles. As Fig. 38.3 show it schematically. It includes an elevation arm whereby friction test functionalities can be implemented by measuring and controlling vertical load over an adjustable force range up to 20 N. The reciprocating motion of the metallic support is generated by a stepper motor which is operated by a programmable controller. Friction forces are measured using a highly sensitive quartz load cell with a maximum resolution 5 mN connected to a charge amplifier. Vertical forces are recorded using a strain-gauge force transducer with a maximum resolution of 10 mN. The position of the manoeuvrable weight can be changed in order to adjust the normal load. The weight is driven by a DC motor. The slider is flat and circular with a diameter of 28.5 mm, which results the surface area of

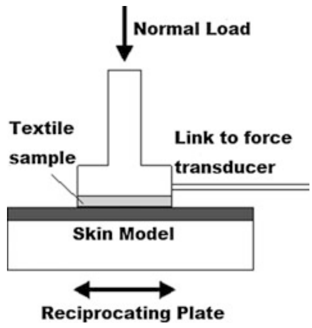

Fig. 38.3 Set-up for friction measurements

about 6.4 cm^2. The MCS samples are attached to the slider by adhesive tapes and rubbed against the reciprocating support covered with a layer of skin models film.

The friction measurements were carried out under dry conditions in a laboratory with standard climate (20 ± 1 °C and 65 ± 2 % relative humidity). All the samples were pre-conditioned for 24 h with the same condition before testing. During the test, the MCS samples remained stationary while the skin model on its metallic support base underwent 550 linear friction cycles with a stroke of 20 mm and using an oscillation frequency of 1.25 Hz. The normal and the friction forces were measured continuously and simultaneously, and, thus, one set of friction data was determined for every 50 cycles.

To determine the load dependence of MCS surfaces, a series of applied normal loads, increasing from 0.5 to 8 N, were investigated in this experiment. The sliding direction is corresponding to the practical use of putting on the stockings which is in warp direction, vertical to the orientation of inlaid yarns.

38.3 Results and Discussions

The coefficient of friction (COF) for MCS against with PUR and Lorica were assessed by rubbing the samples over 550 friction cycles, one typical result of friction coefficients is shown in Fig. 38.4a. Each data point represents the average COF (friction of coefficient) with standard deviation obtained from every 50 cycles.

Figure 38.4b shows the range sliding friction coefficients of MCS with various skin models. The friction coefficients measured from different skin models ranged from 0.80 to 1.92 in MCS/PUR and from 0.30 to 0.77 in MCS/Lorica. The friction coefficients have a significant difference on the two skin models. Compare to MCS contacting with PUR, the range of friction coefficients under MCS/Lorica were narrower and the value of friction coefficients are slower. These findings are in good accordance with the results of previous studies [8].

A pronounced load dependence was observed for the both, the higher friction coefficients were normally found with lower load. It is therefore unreasonable to

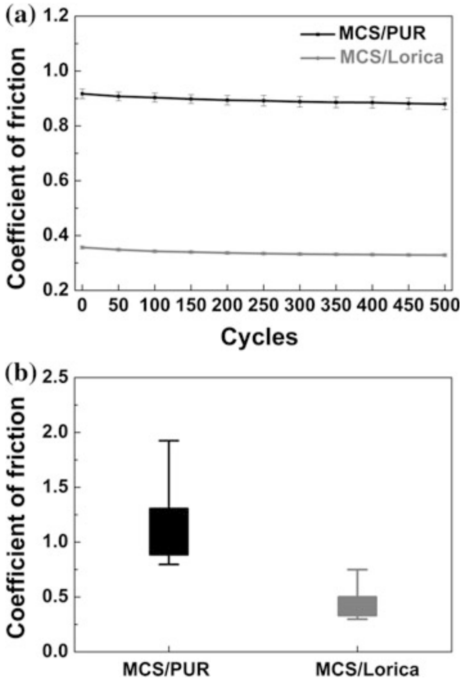

Fig. 38.4 The coefficient of friction (COF) as a function of sliding cycles (**a**) and the range of COF of MCS against PUR and Lorica (**b**)

contribute the difference of MCS/PUR and MCS/Lorica to the variation of skin model materials.

Thus, the influence of normal load on the COF of MCS contacting with various skin models was illustrated in Fig. 38.5. The friction coefficients of both cases investigated systematically decreased with the applied normal load during the friction experiments. It was also showed that it was decreasing rapidly in the lower load form 0.5 to 2 N, followed by relatively constant or stable frictional behaviour. The results can be approximated by a function of the form $\mu(N) = aN^{-\frac{1}{3}} + b$, where μ denotes the friction coefficient, N is the normal load and a, b the fitting parameters. The fitting were plotted in Fig. 38.5 (solid line). Then the friction data can be qualitatively explained by the classical two-term model of friction, corresponding to the common view that the adhesive component of skin friction drops with the normal load to the power of $-1/3$. Therefore, it can be assumed that the adhesion friction were predominate mechanisms in both cases of MCS against with PUR and Lorica.

A stable friction stage was observed for both cases in Fig. 38.5. It can be assumed that the load dependence is not significant on the higher load (2–8 N).The COF with the normal load of 4 N for MCS/PUR and Lorica were calculated as the mean COF of MCS, which is no dependence on the normal force. In this case, the COF of MCS/PUR and MCS/Lorica are 0.89 ± 0.01 and 0.34 ± 0.01, respectively. It can be concluded that the COF of MCS/PUR is higher than MCS/Lorica,

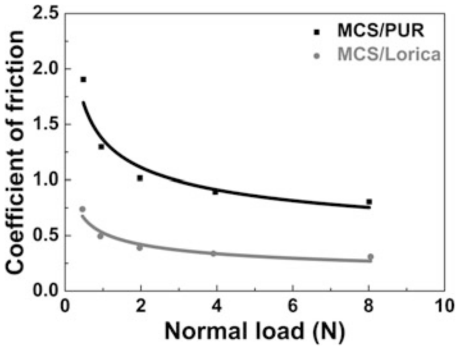

Fig. 38.5 COF as a function of normal load (*dot*) and non-linear fitting (*solid line*). *Black line* (MCS/PUR): $\mu = 0.15 + 1.21 * N^{-1/3}$, *Grey line* (MCS/Lorica): $\mu = 0.02 + 0.51 * N^{-1/3}$

with a factor of 2.6. And the COF of MCS/Lorica is quite close to the value of MCS (0.36 ± 0.04) from in vivo tests in previous study [10], which indicates that the friction coefficient of Lorica is closer to the real human skin.

Combined with Table 38.1, it reveals the trend that rougher materials have lower friction coefficient from the first sight. Due to the rougher the surface, the fewer the contact points, thus the smaller the real contact area. This finding is also consistent with the work of Derler [8], who observed that the smoother skin model surfaces showed higher friction coefficients as a result of an increased contact area. However, there is no qualitatively explanation about the rate of increased real contact area. Furthermore, the roughness of Lorica is around 71 times of PUR, while the COF of PUR is 2.6 times higher, which is nonlinear relationship.

As for elasticity modulus, Lorica is higher than PUR, with a factor of around 2.4, which is in good accordance with the results of COF. Form Hertz contact model and adhesion friction model, $F = \tau A_r \to \mu = F/N = \tau A_r/N = \tau \Pi a^2/N = \tau \Pi \left(\frac{3RN}{4E^*}\right)^{4/3} / N \to \mu \propto E^{*-4/3}$. So it can be concluded that the difference on the elastic modulus of MCS and PUR deduce the variation of COF under MCS/Lorica and MCS/PUR.

38.4 Conclusions

Friction measurements of MCS against with various models in dry conditions have been carried out in the laboratory, to check the differences on the skin models. The skin model Lorica reveals a lower COF, while the COF of PUR is higher, with a factor of 2.6 and Lorica is better to be mechanical skin model candidates for MCS friction testing. The differences on COF between the two models can be attributing to the variation of elastic modulus.

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