Research Article

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Strain-dependent wicking behavior of cotton/lycra elastic woven fabric for sportswear

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Abstract: The strain-dependent vertical and horizontal wicking of as-prepared cotton/lycra elastic woven fabric was systematically studied. The experimental results revealed that the fabric exhibited a strain strengthening effect. A higher tensile strain results in a higher equilibrium wicking height, and vice versa. Moreover, the results indicated that the proposed Laughlin–Davies model is capable of tracking well the experimental data and replicating the wicking characteristics of fabric under different levels of stretch. In addition, the wetting time and wicking area of fabric under different strains and height regimes were examined during horizontal wicking. It was found that the wetting time decreased with an increase of strain and/or water drop height. The strain-enhanced and height-weakened effects of wicking area were revealed. The spreading mechanism of water drop in elastic fabric was also proposed. Such fundamental work provides a basic support for the in-depth investigation of wicking behavior of complex stretchable textile structures.

Keywords: wicking, wicking model, moisture management, strain-dependent, elastic fabric

1 Introduction

In recent years, we have witnessed the rapid development in the manufacture of elastic fabric structures including woven and knit. Elastic fabrics and their garments have the ability to stretch easily and to return back to their original shapes quickly (1). To prepare elastic fabrics, the elastane filaments and the relevant specifications such as linear density and draw ratio need to be taken into account because they specify the final structural configuration of elastic yarns and the resultant fabrics (2,3). The elastane-based textile materials have been widely used in strenuous sportswear and help to improve oxygen uptake in human muscles and bring down the levels of lactate within blood (4). As a result, it is of practical significance to develop fabrics with desired stretchability and systematically clarify the structural-property relationship.

Wicking, a crucial characteristic, which directly determines the moisture management of fibrous assemblies, has a major impact on the physiological comfort of textiles (4,5). As such, controllable moisture management is viewed as a major factor in the development of elastic fabrics. Wicking in textile materials is the spontaneous transports of a liquid, driven by capillary action (6). Prior to the present research, an approximate flow equation in fibrous assemblies was given by Laughlin and Davies (7). The classical Lucas–Washburn kinetics analysis model to describe wicking length vs wicking time relationship was reported by Washburn (8). The vertical and horizontal wicking behavior and drying capability of functional knit fabrics were investigated by Fangueiro et al. (9). Chen et al. pointed out that the water diffusion time significantly decreased with an increase of water drop height, and the water drop volume also exerted a large effect on water diffusion time (10). A self-made computerized wicking tester was built to investigate the in-plane wicking behavior of fibrous assemblies, and it was found that the wicking rate and the amount of spreading of liquid flow on fabric surface were dependent on the fiber type (11). Mhetre and Parachuru pointed out that the rate of liquid migration between the longitudinal and transverse yarns was a crucial factor in deciding the wicking in woven fabrics (12). In brief, a minor review of literature reveals that liquid transfers in textiles including vertical and/or horizontal wicking are mainly determined by

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several factors, such as fiber type, number of fibers in yarn cross section, yarn structure, yarn roughness, effective capillary pore sizes and geometric distribution within a fabric, liquid characteristics, finishing treatments, etc. Currently, despite extensive studies of fabric wicking in quasi-static state, to the best of our knowledge, very little work that focuses on the wicking behavior for elastic fabric under different levels of stretch can be found.

In this work, we examined the vertical and horizontal wicking properties of as-prepared cotton/lycra elastic woven fabric in tension (i.e., at different tensile strains), in order to obtain a deep understanding of the effect of tensile strain on the final wicking behavior. Such work provides basis support of elastic fabrics under a realistic stretch regime.

2 Experimental procedures

2.1 Materials

Herein, the cotton fibers with mean fineness of 1.4 dtex, mean length of 30.8 mm, and break tenacity of 29.8 cN/tex were employed to prepare cotton roving of 450 tex. A lycra filament of 40 denier was used as the elastic component.

2.2 Preparation of elastic core-spun yarn

The elastic core yarn was prepared on a modified ring spinning frame, which was elaborately retrofitted with a grooved roller and positive feed rollers, as per the work by Wang et al. (13), as graphically shown in Figure 1a. The continuous lycra filament was stretched using positive feed rollers and the staple cotton fibers were passed through normal drafting arrangement. The drawn lycra filament was stable at the center of the spinning triangle zone and could be covered with staple cotton fibers completely. The key spinning variables are as follows: total draft/break draft 24.68/1.20, draw ratio of lycra filament 2.5, twist 680 T/m, and spindle speed 8,500 rpm. An elastic core yarn was finally formed. The elastane core stretching was performed to maintain the stretchable elasticity of the yarn because of the retraction of the core when yarn stress was reduced or removed, as shown in Figure 1b. Also, we saw that the lycra was positioned in core and was wrapped with cotton fibers when the elastic yarn was partially untwisted.

2.3 Preparation of cotton/lycra elastic woven fabric

To explore the sportswear use of our elastic core yarn, a 3/1 twill elastic woven fabric was prepared with a count of 170 ends/in × 93 picks/in by using a CCI Studio automatic rapier loom. The weft and warp are the above elastic core yarn of 20 tex and the normal cotton yarn of 18.22 tex, respectively. After that, the fabric was washed by mild detergent, hang to dry, and subjected to mild ironing before subsequent testing (see flow chart in Figure 2a). In addition, as displayed in Figure 2b, the letter-pattern “I ♥ AHPU” marked on fabric surface reveals the capacity of fabric to be extended substantially.

Figure 1: (a) Schematic diagram of elastic core-spun yarn production on a modified ring-spun frame. (b) Appearances of an elastic core yarn sample in stretched and initial states, respectively.
in its weft direction. Also, the angle of inclination of fabric surface changed from 62° in initial state to 55° in stretched state.

2.4 Characterization

All the wicking tests of elastic fabric were carried out in ambient temperature of 25 ± 2°C and relative humidity of 65 ± 3%.

2.4.1 Vertical wicking

2.4.1.1 Experimental

A self-made apparatus was built to investigate the fabric vertical wicking, as illustrated in Figure 3. The vertical wicking height of as-prepared elastic fabric was measured based on China standard FZ/T 01071-2008. Strip fabric samples (30 mm width × 150 mm length) under different levels of stretch were immersed into a liquid reservoir containing distilled water, and a few drops of potassium dichromate solution were added to enhance the observation of liquid movement. Effect of colored solution on fabric wicking can be neglected ([14,15]). A steel ruler was used to measure the wicking height. The whole wicking process was recorded in 5 min by using a digital camera. Images were then extracted from the video files using Adobe Premiere Pro 2020. The image brightness was adjusted to enhance the contrast of liquid front, and the wicking height was measured at the center-line position of the liquid front. Three replicates were tested for each condition.

2.4.1.2 Description of wicking models

In general, the Lucas–Washburn wicking model is used to describe the liquid transport behavior of simple cylindrical-shape tubes, and the relationship between the height reached and wicking time is in accordance with a square law empirically ([16–19]):

\[ h = C t^{0.5} \]  \hspace{1cm} (1)

where \( h \) is vertical wicking height at time \( t \), \( t \) is the given wicking time, \( C \) is the coefficient of capillary rise. As per the work by Laughlin and Davies ([7]), \( C \) is closely related to the ultimate height reached by the fluid in infinite time \( h_{\text{max}} \) (which is determined by the balance between the upward forces of capillary action and the downward forces of gravity), the capillary radius \( R \), the gravitation constant \( g \), the fluid density \( d \), and \( \eta \), the liquid viscosity.

Since the macro–micro capillaries of fibrous textiles are not geometrically equivalent to a cylindrical tube, Eq. 1 does not hold in general. To obtain a best fit of the experimental curve, a time exponent \( k \) \( (k > 0) \) was introduced as follows ([7,17]); we call it Laughlin–Davies wicking model:

\[ h = C' t^k, \quad (k > 0) \]  \hspace{1cm} (2)

2.4.1.3 Numerical simulation and assessment

To reveal the underlying wicking mechanism, numerical simulation was conducted using Levenberg–Marquardt

Figure 2: (a) Fabrication procedure and (b) stretchability of as-prepared cotton/lycra elastic fabric.

Figure 3: (a) Schematic diagram and (b) real photo of experimental setup for fabric vertical wicking.
algorithm with 1stOpt software. Three statistical criteria, i.e., correlation coefficient ($R$), average-absolute-relative error (AARE), and root-mean-square error (RMSE), were used to assess the fitting aptness (15).

$$R = \frac{\sum_{i=1}^{N} (E_i - \bar{E})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{N}(E_i - \bar{E})^2 (P_i - \bar{P})^2}}$$  \hspace{1cm} (3)$$

$$\text{AARE} \, (\%) = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{E_i - P_i}{E_i} \right| \times 100$$ \hspace{1cm} (4)$$

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (E_i - P_i)^2}$$ \hspace{1cm} (5)$$

where $E_i$ and $P_i$ are the experimental and predicted value, and $ar{E}$ and $ar{P}$ are the mean values, respectively; $N$ is the total testing number.

2.4.2 Horizontal wicking

The horizontal wicking performances of elastic fabric were systematically studied with the aid of an injection pump system (ZS100 model; Chuangrui Precision Pump Co., Ltd). As shown in Figure 4a, an elastic fabric strip was tightly fixed by two clamps, and the syringe needle containing potassium dichromate was arranged right above the fabric with established height. A water drop is allowed to fall from a height onto fabric surface based on AATCC 79-2014. The time required for water drop to lose any light reflection and change to a dull, wetted spot is called “wetting time.” A digital camera mounted on top of the syringe needle was used to record the whole process. Finally, two indices, i.e., the wetting time and wicking area, can be obtained with the aid of Adobe Premiere Pro 2020 and ImageJ softwares, respectively. Two cases were performed as follows, three replicates were tested for each case:

- Case I: As shown in Figure 4b, the stretch level of elastic fabric was changed from 0%, 10%, and 20% with a constant drop height of 12 cm.

- Case II: As shown in Figure 4c, the drop height was changed from 4, 8, and 12 cm, while keeping the elastic fabric in freeload state (i.e., 0%).

3 Results and discussion

3.1 Vertical wicking behavior of elastic fabric

3.1.1 Model optimization of fabric vertical wicking

Figure 5a shows the vertical wicking height of elastic fabric in initial state (0% stretch) as a function of wicking time. According to the character of wicking height vs time curve, the wicking process can be mainly divided into two stages. As expected, the penetrating velocity of liquid in the early stages of wicking is much higher than that in subsequent stages (14,15). The advancement of liquid water becomes slower and slower over wicking time until an approximately equilibrium state is obtained. Furthermore, the curve of wicking rate vs time in the inset of

![Figure 4](image_url)

Figure 4: (a) Experimental setup for fabric horizontal wicking. (b and c) Sketch of fabric horizontal wicking as a function of tensile strain and drop height, respectively.
Figure 5a confirmed this. The rate of liquid raise for elastic fabric was initially faster (0–10 s), but slowed down with a further increase of wicking time. The highest wicking rate of fabric in freeload state reaches 1.5 mm/s at the early time, whereas the wicking rate is close to zero with increasing wicking time.

Figure 5b presents the experimental and predicted curves based on two wicking models proposed above. By contrast, the proposed Laughlin–Davies model can offer a fairly reasonable evolution of fabric wicking performance, and the shape progression goes hand in hand with the experimental curve, whereas the Lucas–Washburn wicking model shows certain deviation. Also, the statistical indices were summarized in the inset, the results of which further confirmed the fitting aptness of Laughlin–Davies wicking model for describing fabric wicking characteristics. In addition, several consecutive captured images of fabric with freeload with increasing wicking time were shown in Figure 5c, which can better illustrate the relationship between wicking height and wicking time.

3.1.2 Strain-enhanced effect of vertical wickability

Figure 6a presents the vertical wicking heights of elastic fabric at different elongations (0%, 10%, and 20%) as a function of wicking time. It was found that the wicking height increased with an increase of elongation. The captured images of fabric at wicking time of 150 and 300 s, respectively, have confirmed this, as seen in inset. The results in Figure 6b showed that a higher wicking rate of fabric during stretch was found, and the highest wicking rate reaches 2.5 mm/s at a tensile strain of 20%.

Why the equilibrium wicking height increases when as-prepared cotton/lycra elastic fabric was stretched? Also the wicking rate? The underlying mechanism was unraveled as follows. Fabric wicking is primarily determined by the wicking behavior of its constituent yarns, fabric structure including the yarn spacing and the rate of liquid migration between the longitudinal and transverse yarns, etc. (9,12). The tightness of fabric structure plays a crucial role in deciding the final wicking nature. As seen in Figure 6c, our elastic fabric gets relatively looser when...
stretched, and hence, results in a larger size of pore structure; they offer less resistance to water rise (20). Furthermore, when a strip of our fabric along weft direction is immersed in a liquid, the liquid first starts to spread through weft yarns. The distance of adjacent warp yarns of fabric enlarged when stretched; in this case, the chance of the traveling liquid along weft yarns encounters warp yarns reduced, and thus the amount of liquid in weft yarns moved into warp yarns reduced (21). Consequently, the wicking height can go up. In addition, the inter-yarn spaces exerted a large effect on the fabric wicking behavior. There is a direct relation between wicking features and packing density of fibrous assemblies (6,17). An increased packing density of weft yarns was obtained when the fabric was stretched, which results in smaller inter-yarn spaces suitable for wicking. In short, based on the above detailed analysis, stretching plays an important role in determining the moisture management of textiles (4), and the equilibrium wicking height of cotton/lycra elastic woven fabric during stretch increases accordingly.

To validate the selected Laughlin–Davies wicking model, the vertical wicking of fabric under different levels of stretch was numerically simulated, the results of which are given in Figure 6d. As can be visibly seen, the predicted wicking height is capable of tracing well the experimental data for the entire range of tensile strain and expressing the wicking features. Furthermore, the wicking curve is substantially sensitive to tensile strain and shifts toward the wicking height axis when the test is conducted at a higher tensile strain, demonstrating an increasing wicking rate of fabric with elevated elongations. In addition, the reliability of predictions was evaluated using the three statistical indices, the results of which are presented in the inset.

Figure 6: (a and b) Wicking heights and wicking rates of elastic fabric at different elongations. (c) Schematic diagram of fabric wicking behavior during stretch. (d) Predicted curves of fabric at different elongations using Laughlin–Davies wicking model.
3.2 Horizontal wicking behavior of elastic fabric

3.2.1 Strain effect of horizontal wicking

As seen in Figure 7a, an increase of applied tensile strain resulted in a decreased wetting time gradually. The wetting time decreased from 3.22 s at strain of 0% to 2.37 and 2.01 s, when the elongation increased to 10% and 20%, respectively. However, the wetting time found no significant difference at higher heights of water drop, for instance, the relative error was less than 2.5% between heights of 8 and 12 cm.

When a drop of water is placed on a fabric surface, it will spread horizontally under the capillary forces. The spreading process may be divided into phases I and II (22), as shown in Figure 7c. The liquid remains on fabric surface at certain stages, and at some stages, it is completely contained within the fabric. The area of wicking spot is analyzed every 0.3 s, and the results are depicted in Figure 7b. The data have a bilinear manner (i.e., each curve presents two straight lines), which means that the slope of wicking area data changed drastically at exact wicking time level. The first straight line represents the liquid spreading during phase I, and the second line that during phase II. By contrast, the wetting time during phase I is relatively shorter, and the time of 0.6 s is considered a turning point. Furthermore, the wicking area and wicking rate of fabric increased with an increase of stretch. The captured images in Figure 7d proved well the above results. The water drop gradually turned into a dull, wetted spot.

3.2.2 Height effect of horizontal wicking

As shown in Figure 8a, an increase of liquid drop height resulted in a decreased wetting time gradually. The wetting time decreased marginally from 4.11 s at 4 cm drop height to 3.35 and 3.22 s, when the height increased to 8 and 12 cm, respectively. Higher drop height caused a larger gravity force which drives liquid to transport along the fabric, and hence, results in a shorter wetting time. However, the wetting time found no remarkable difference at higher heights of water drop.
Similarly, the spreading process of elastic fabric irrespective of drop heights considered can be divided into phase I and phase II (22). Figure 8b shows the average wicking area as a function of wicking time. The wicking time during phase I is relatively shorter (here, it refers to 0.6). Furthermore, the characteristics of wicking area vs wicking time were not obvious compared with these at different elongations. On the whole, by contrast, the wicking area decreased, whereas the wicking rate increased marginally with the increase of drop heights.

4 Conclusion

The strain-dependent vertical and horizontal wicking behavior of our as-prepared cotton/lycra elastic woven fabric was investigated in this paper. The following conclusion can be drawn:

A combined experimental and modeling investigation has been performed to elucidate the vertical wicking properties of elastic fabric at different elongations. On the experimental side, the fabric exhibited a strain strengthening effect. The higher the strain, the higher the wicking height. On the analytical side, the feasibility of Laughlin–Davies model describing the strain-dependent fabric wicking characteristics was validated. With respect to the horizontal wicking, the wetting time decreased with increasing strain and/or liquid drop height. The wicking area increased as a function of wicking time, and the strain-enhanced and height-weakened effects of wicking area were revealed. Moreover, the spreading mechanism of water drop in fabric is initially retention of liquid on fabric surface and gradual spreading until it is completely diffused within the fabric.

For elastic fabric structures, the wicking behavior depends on several factors; apart from tensile strain, environmental conditions such as temperature and relative humidity on fabric wickability should be clarified. Furthermore, as a popular textile fabric used for sportswear, apart from the wicking characterization, the mechanical behavior including elasticity of such fabric also needs to be systematically studied. There remains a myriad more combinations of elastic element, yarn, and fabric structures that need to be further determined to optimize the design, and finally prepare fabrics having both superior wicking properties and excellent reversible stretchability. Such fundamental work is essential to get a comprehensive evaluation of our as-prepared elastic woven fabric.

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