Quantifying the effects of external factors on the behavior of vertical wicking in a warp stretch woven fabric

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Abstract
Wicking ability of textiles is a key indicator in determining the physiological comfort provided by a fabric. The property is shaped by various factors internal and external to the fabric. Herein, the effects of some external factors such as the degree of (fabric) extension, the wetting liquid's temperature and relative humidity on the vertical wicking behavior of a previously prepared warp stretch woven fabric were investigated. The fabric, which could be reversibly extended up to 60%, was prepared using a nylon/spandex air-covered yarn in the warp and cotton yarn in the weft. The results indicated that these external factors had a great influence on the vertical wicking equilibrium height with the degree of fabric extension having a more pronounced effect compared with the other two factors. Furthermore, extension and relative humidity were negatively related to the height of the vertical wicking, whilst an increase in liquid temperature resulted in an increase in vertical wicking height. The underlying mechanisms associated with these effects were examined using a specially constructed test chamber and tensioning device. The experimental data were also verified using the classical Laughlin-Davies model, and the results demonstrated the proposed wicking model could be used to predict the changes in fabric wicking height. These findings provide a more in-depth understanding of the wicking behavior of stretchable textiles in a comprehensive and objective manner.

Keywords
Warp stretch woven fabric, wicking height, external factors, stretchability, liquid temperature, relative humidity

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Introduction
It is generally accepted that liquid/moisture transport into a textile fabric is a key indicator in determining the physiological comfort provided by a fabric, especially for the use in sportswear and underwear. Functional textiles including elastic fabrics have been used extensively in many applications including but not limited to leisure wear, flexible composites, tissue engineering, protective devices, and smart textiles.1–4 Maintaining and improving the use of stretchable materials in these applications, and in particular in sports and leisure wear, requires the development of new technologies that can improve the comfort and performance of these fabrics. What is needed is a deeper understanding of the mechanisms by which liquid transport occurs within stretchable fabrics. In this regard, the quantification of wicking behavior is critical for the development of functional textiles.

The wicking height, which is the distance a wetting liquid travels through a fabric, is a key indicator of the comfort provided by a fabric and is shaped by various factors, both internal and external to the fabric. The wicking height is influenced by the fiber material, yarn structure, and fabric construction, as well as external factors such as the temperature and relative humidity of the environment. Therefore, it is important to develop a comprehensive understanding of the factors that influence wicking behavior in stretchable fabrics.

The present study aimed to investigate the effects of external factors such as the degree of extension, the wetting liquid's temperature, and relative humidity on the vertical wicking behavior of a stretchable warp stretch woven fabric. The fabric was prepared using a nylon/spandex air-covered yarn in the warp and cotton yarn in the weft. The results indicated that these external factors had a great influence on the vertical wicking equilibrium height with the degree of fabric extension having a more pronounced effect compared with the other two factors. Furthermore, extension and relative humidity were negatively related to the height of the vertical wicking, whilst an increase in liquid temperature resulted in an increase in vertical wicking height. The underlying mechanisms associated with these effects were examined using a specially constructed test chamber and tensioning device. The experimental data were also verified using the classical Laughlin-Davies model, and the results demonstrated the proposed wicking model could be used to predict the changes in fabric wicking height. These findings provide a more in-depth understanding of the wicking behavior of stretchable textiles in a comprehensive and objective manner.
the comfort of stretch fabrics remains a goal for fabric manufacturers, given the close skin contact of these materials in various applications, and the hydrophobic nature of the elastane filaments that provide their stretch. Comfort afforded by these types of fabrics can be improved by understanding the physical liquid transport mechanisms. Due to the relatively complex macro/microstructures of elastic fabrics, particularly the change of pore dimensions when stretched, an insight of the liquid transport behavior of these fabric structures remains a challenging issue.

Much research work has been done to investigate the liquid transport mechanisms in textiles of various forms. At the fiber scale, properties that affect wicking ability include fiber type, in terms of its polymer make-up, structural geometry and chemical treatments applied pre- or post-fabric manufacture. For example, Wang et al. studied the wettability of carbon fibers composed of unsized and sized fibers at micro- and meso-scales, and quantified how modification of the surface chemistry at the micro-scale transferred directly to the meso-scale. Kan and Yuen revealed the longitudinal wicking performance of synthetic fibers, for example, polyester and polyamide, was improved after atmospheric pressure plasma treatment to their surfaces. Stuart et al. pointed out the wicking of liquid through viscose fibers was mainly via inter-fiber capillaries while wicking through flax was a combination of the inter-fiber capillaries and the fiber lumen present in some elementary fibers. Glavan et al. reported that the wicking of profiled polyester fibers was dependent on the micro/macro-fiber profiled structures of the fibers.

At the yarn scale, the parameters that affect wicking include fiber type, for example, whether the fiber polymer is hygroscopic, structural geometry, yarn count, twist, and any tension applied to the fabric. For instance, Yoiti Ito Parada et al. pointed out that the water filling over the height of the yarn is highly non-uniform, since the available pore space varies strongly along the yarn due to the twisting of the yarn. Liu et al. investigated the wicking of twisted yarns, and they pointed out with an increase of twist, the equilibrium vertical wicking height of yarn decreases. Effects of yarn count and twist factor on the packing density of fibers and the wicking equilibrium height of lyocell ring-spun yarns were studied by Taheri et al. The influence of fatigue loading on the wickability of polyamide 66 nanofiber yarns was clarified by Asghari Mooneghi et al., who found that applying a cyclic (stretch) loading to the yarn increased the equilibrium wicking height. The vertical wicking behavior of a ring-spun composite yarn of varying twist and subject to different extensions was studied by Wang et al. Twist-weakened and extension-enhanced wicking effects were observed within the testing range.

At the fabric scale, parameters that affect wicking rates are yarn type, weave or knit structures and process history, finishing treatments and again external factors, such as applied extension and the ambient conditions under which the measurement is made. A range of different fabric types have been investigated. For example, Cimilli Duru and Şahin studied the effects of yarn type, for example, Sirospun, ring, or open-end, process history, softener type on the wicking and drying ability of plain knit cotton fabrics. They found that fabrics made from siro yarns tended to perform better. Dyeing process caused enhanced the wicking and drying behavior. However, softener such as silicone has a negative effect. Lei et al. investigated the effect of weaving structures (e.g. with different floats) on the wicking performance of woven fabrics. The wicking behavior of cotton jersey, rib, and interlock knitted fabrics under different deformation state was investigated by Priyalatha and Raja, who found that the area of wicking is higher in front than back side of fabric at any given period of time, and the fabric wicking under dynamic condition has been increased than the static condition. Recently, Wang et al. pointed out the wicking properties of an elastic cotton/lycra woven fabric were closely related to various external factors such as the extension applied, the temperature of the wetting liquid and the relative humidity. However, to the best of our knowledge, little work has been performed investigating thewickability of warp stretch fabric structures under different external conditions.

To this end, the present work attempts to investigate the effect of some external factors (e.g. tensile extension, liquid temperature, and relative humidity) on vertical wicking performance of a previously prepared warp stretch woven fabric. The objective of this work is to provide a better understanding of the wicking behavior of stretchable textiles.

**Experimental**

**Raw materials**

Cotton fibers of 140 mtex and 30.8 mm were used to prepare ring-spun cotton yarn of 58.3 tex. A nylon multifilament of 70 denier/24f was purchased from Jiangsu WenFeng Chemical Fiber Group Co., Ltd., China and a spandex of 40 denier was purchased from Haining Kaiwei Textile Co., Ltd., China.

**Manufacturing of a highly warp stretch woven fabric**

A warp stretch woven fabric was manufactured as per our previous work. Figure 1(a) illustrates the fabrication procedure of the warp nylon/spandex air-covered yarn used in the fabric. The following parameters were replicated as follows; a draw ratio of 2.0 was used to introduce the spandex filament with a nominal pretension of 5–8 cN applied
to the nylon multifilament. An air pressure of 600 kPa was applied through the air-nozzle to apply the spandex around the nylon filament. The yarn delivery speed was set at 115 m/min. The final nylon/spandex yarn had intermittent nodes of slack yarn loops distributed along its axis providing an extensible capacity of about 200%.

The above yarn was used in the warp direction to weave a 2/1 left twill fabric of 32 ends/cm × 39 picks/cm. A cotton yarn of English count Ne 10 (58.3 tex) was used in the weft direction. The resulting fabric could be reversibly extended to a high strain of about 62% in warp direction as per Figure 1(b). Notable was that micropores in the extended fabric were evenly distributed.

**Vertical wicking characterization**

The warp stretch woven fabric was allowed to condition and relax under zero tension for at least 24 h in ambient temperature of 25 ± 2°C and relative humidity of 65 ± 3% before testing.

**Experimental test procedure.** The vertical wicking behavior of the prepared warp stretch woven fabric was measured based on the Standards FZ/T 01071-2008 and EN ISO 9073-6:2003. Strip fabric samples of 250 mm length × 30 mm width were prepared along the warp direction of a fabric, and then one of the samples was tightly fixed to a middle-hollow plastic framework and vertically hung alongside a steel ruler with its lower end immersed in a liquid reservoir containing colored distilled water. The whole process was recorded using a camera over a 5 min period. Wicking height at intervals of time was then analyzed using Adobe Premiere Pro 2020 and ImageJ to provide data to graph wicking height versus time behavior.

To clarify the effects of external factors, for example, such as tensile extension, liquid temperature and environmental relative humidity on vertical wicking ability of prepared fabric, an experimental chamber as illustrated in Figure 2 was constructed. Figure 2(a) shows the experimental chamber and setup built to measure fabric wicking height under three different liquid temperatures, that is, 25°C, 45°C, and 65°C, and three relative humidity levels, that is, 25%, 65%, and 95%. A hot plate was employed to adjust and maintain the liquid temperature, and a humidifier was used to adjust the relative humidity inside the chamber. Note that for the low humidity settings, that is, 25%, a hot air dryer and humidifier were used together. Figure 2(b) shows the plastic frame and fabric clamps constructed to measure the wicking height under four different extension levels, that is, 0%, 20%, 40%, and 60%. Five replicates were tested for each event.

**Mathematical models to predict vertical wicking profile.** An objective of this study is to formulate and test a model upon which close predictions about the vertical wicking behavior of warp stretch woven fabric can be made. The wicking models of textile materials serve as a bridge between capillary microsystem and macroscopic wicking phenomenon. Researchers use different theoretical models to analyze the liquid flow within a textile, for example, capillary force model, wicking pressure model and energy model, etc. The wicking process has been described by structural information of fibrous materials, such as
porosity, size, pore distribution, etc. Currently, the most widely used wicking model is Lucas-Washburn equation, and it assumes that the pores inside a porous material are arranged in parallel and traverse the length of the porous material\(^{22}\)

\[
h = \frac{r \gamma_{LA} \cos \theta}{2 \eta} t^{0.5} = C t^{0.5}
\]

(1)

\[
C = \frac{r \gamma_{LA} \cos \theta}{2 \eta}
\]

(2)

According to equation (1), we can see that, for a given fabric, the main influencing factors of wicking height \((h)\) are decided by the radius of the pore \((r)\), along with other factors, including liquid surface tension \((\gamma_{LA})\), contact angle \((\theta)\), and liquid viscosity \((\eta)\), which remain unchanged. Moreover, according to equation (2), the coefficient of capillary rise rate \((C)\) is closely related to the values of \(r\), \(\gamma_{LA}\), \(\theta\) and \(\eta\), respectively. The radius \(r\) is not the actual radius of yarns or the gap between adjacent yarns within a fabric, it refers to the cylindrical capillary effect radius. Thus, we need to analyze which factors of the prepared warp stretch fabric can affect the actual effective water-absorption radius.

For the as-prepared stretch fabric, at the yarn level, since the yarn is not a cylinder, the capillary radius of the yarn should be appropriate radius of the void between the fibers in a yarn. At the fabric level, since the macro/micro-structures of fibrous fabrics tend to be tortuous, apart from the capillary radius at the yarn level, the created pores or gaps between the adjacent yarns within a fabric should also be responsible for the effective capillary radius. As a result, in this work, the Laughlin-Davies model (equation (3)), in which a time exponent \(k (k > 0)\) is introduced to provide an additional variable in the vertical wicking model of staple fiber based fabrics\(^{13,17,18}\)

\[
h = C' t^k \quad (k > 0)
\]

(3)

Results and discussion

Tensile extension effect

To explore the effect of tensile extension level on the vertical wicking behavior of fabric, the samples were clamped into the device and placed at a water bath of constant liquid temperature \((25^\circ C)\) and relative humidity \((65\% \, RH)\) and subject to different rates of extension. The wicking height (in mm) and the wicking rate (in mm/s) were recorded. The results are plotted in Figure 3(a) and (b). The results show wicking height increased as a function of wicking time, irrespective of tensile extension considered, albeit that the final height and wicking rates were reduced when the fabric was extended more than 20%. For example, the wicking equilibrium height of fabric at 0% extension reached 53.5 mm whereas the wicking height at an extension of 60% was only 5.5 mm. The consecutive images of fabric at strains of 0% and 40% confirmed this (Figure 3(c)). Generally, the rate of liquid raise was initially faster, but slowed down with increasing time, irrespective of extension applied. The highest wicking rate at extension of 0% reaches 0.5 mm/s at the initial time, whereas it is close to zero with a further increase of wicking time.
Furthermore, the tensile extension-weakening wicking mechanism of the fabric was unraveled. Figure 3(d) illustrates the structural deformation of fabric during warp stretch as captured using an USB digital microscope. The distance between the adjacent weft cotton yarns increased when stretched, from 0.276 to 0.448 mm under extensions of 0% and 40%, respectively. From this point of view, a “sparse/dense” structured ladder model was used to illustrate the difference of wicking ability. An increase in pore radius (and the corresponding increased pore area) will cause a reduction in the capillary pressure, which is responsible for the poor wicking ability of fabric when

![Figure 3.](image-url)
stretched. We can also conclude from this that it is crucial to take into consideration the variability of fabric structure while discussing the wicking behavior of textile fabric.

In addition, the proposed Laughlin-Davies model was used to represent the wicking evolution of the prepared stretch fabric using the Levenberg-Marquardt algorithm with 1stOpt software, and the results were presented in Figure 3(e). The results indicated that the proposed wicking model could be used to predict changes in fabric wicking height. Also, the statistical parameters, for example, coefficient of determination ($R^2$) and root-mean-square error (RMSE) were summarized. As is expected, the values of $R^2$ of fabric at each extension level were found to be above 0.983, and the values of RMSE were relatively low.

Liquid temperature effect

To explore the effect of wetting liquid's temperature on the vertical wicking behavior of fabric, the samples (with freeload) were clamped into the device and placed at a water bath of varying liquid temperatures and relative humidity of 65%. The wicking height (in mm) and the wicking rate (in mm/s) were recorded. The results are plotted in Figure 4(a) and (b). The results show that the wicking height increased as a function of wicking time, irrespective of liquid temperature considered. Moreover, the advancement of liquid along fabric surface at temperatures of 45°C and 65°C is much faster than that at a temperature of 25°C. For example, the equilibrium height of fabric at 65°C reached 67 mm whereas the wicking height at 25°C was 53.5 mm. Generally, the rate of liquid raise was initially faster, but slowed down with an increasing wicking time, irrespective of liquid temperature considered. The highest wicking rate at temperature of 65°C reaches 1.2 mm/s at the initial time, whereas it is close to zero finally. Similarly, the results in Figure 4(d) demonstrate that the proposed Laughlin-Davies model can represent fabric wicking evolution qualitatively and quantitatively. Also, the corresponding values of $R^2$ were found to be above 0.984.
Furthermore, the liquid temperature-strengthening wicking mechanism of fabric was unraveled, as graphically illustrated in Figure 4(c). On the one hand, the diffusion coefficient of liquid water is temperature dependent, and the Arrhenius equation can be used to interpret the influence law. With an increase of liquid temperature, the Brownian motion of liquid molecules becomes more active, which intensifies the thermal motion and mutual collision of molecules. Consequently, the internal energy increases. In this case, the molecules deviate from initial position, and the mutual interaction force reduces, which is conducive to the liquid diffusion. In other words, the increased diffusion coefficient of liquid molecules across capillary pores is responsible for the enhanced wickability with elevated temperature. In the other hand, the capillary absorption coefficient of liquid increases with an increasing temperature. In conclusion, the enhanced temperature-dependent wickability of fabric is the combined effect of the above two factors.

**Environmental relative humidity effect**

To explore the effect of wetting liquid’s temperature on the vertical wicking behavior of fabric, the samples (with free-load) were clamped into the device and placed at a water bath of liquid temperature (25°C) and different relative humidity levels. The wicking height (in mm) and the wicking rate (in mm/s) were recorded. The results are plotted in Figure 5(a) and (b). The results show that the wicking height increased as a function of wicking time, irrespective of relative humidity considered. Moreover, the advancement of liquid along fabric surface at 25% RH is faster than those at 65% and 95% RH. Generally, the rate of liquid raise was initially faster, but slowed down with an increasing wicking time, irrespective of liquid temperature considered. Similarly, the results in Figure 5(d) demonstrate that the proposed Laughlin-Davies model can replicate vertical wicking characteristics of fabric qualitatively and quantitatively. Also, the corresponding values of $R^2$ were found to be above 0.995.
Furthermore, the relative humidity-weakening wicking mechanism of fabric was unraveled, as illustrated in Figure 5(c). On the one hand, for an enclosed space, it can be artificially divided into two zones: high humidity zone (here, it refers to liquid solution) and low humidity zone (here, it refers to the air layer). According to the molecular diffusion transfer mechanism, the liquid molecules will diffuse or permeate from high humidity to low humidity spontaneously, until the concentration of liquid is evenly distributed in this enclosed space. Compared with the high humidity containing more water molecules in gas, the diffusion is more likely to happen under low humidity condition. That is to say, the equilibrium wicking height of fabric decreases with an increase of relative humidity. On the other hand, more liquid fog particles in a high humidity atmosphere are more likely to be absorbed and penetrated into the internal gaps or amorphous areas of fibers. In this case, when the fabric is placed in a liquid reservoir, the liquid does not easily further penetrate into the internal part of fabric, which in turns, resulting in poor wicking ability. In short, the weakened relative humidity-dependent wickability of fabric is the combined effect of the above two factors.

**Conclusion**

Since the wickability of textiles is shaped by internal and external factors, and yet despite this, the external factors are often ignored. For this, the effects of external factors such as the degree of fabric extension, wetting liquid’s temperature and relative humidity on the vertical wicking behavior of a previously prepared warp stretch woven fabric were studied. The fabric, which could be reversibly extended up to 60% without obvious distortion, was manufactured using a nylon/spandex air-covered yarn in the warp and cotton yarn in the weft. These external factors had a great effect on the vertical wicking equilibrium height, and the extension effect is more pronounced compared with the other two factors. From a technological point of view, we can conclude from this that it is crucial to take into consideration the variability of fabric structure. An increase in pore radius (and the corresponding increased pore area) will cause a reduction in capillary pressure, which is responsible for the poor wicking ability of fabric when stretched. Moreover, the liquid temperature was positively related to the vertical height (strengthen effect), whereas the relative humidity had a negative relation (weaken effect). In addition, the results indicate that the Laughlin-Davies model can represent fabric wicking evolution qualitatively and quantitatively. These findings provide an end-to-end understanding of the wicking behavior of stretchable textile fabrics.

In the next step, colored distilled water could be replaced with saline water in order to stimulate the actual sweats. In addition, we aim to establish more accurate and applicable wicking models to predict the vertical equilibrium height and represent the wicking evolution characteristics of fabric taking into account variable fabric structures and some external influencing factors in a more comprehensive and objective manner.

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