In-Vivo Human Skin to Textiles Friction Measurements

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Abstract. We report on a measurement system to determine highly reliable and accurate friction properties of textiles as needed for example as input to garment simulation software. Our investigations led to a set-up that allows to characterize not just textile to textile but also textile to in-vivo human skin tribological properties and thus to fundamental knowledge about genuine wearer interaction in garments. The method of test conveyed in this paper is measuring concurrently and in a highly time resolved manner the normal force as well as the resulting shear force caused by a friction subject intending to slide out of the static friction regime and into the dynamic regime on a test bench. Deeper analysis of various influences is enabled by extending the simple model following Coulomb’s law for rigid body friction to include further essential parameters such as contact force, predominance in the yarn’s orientation and also skin hydration. This easy-to-use system enables to measure reliably and reproducibly both static and dynamic friction for a variety of friction partners including human skin with all its variability there might be.

1. Introduction

The single most productivity enhancing tool for rapid prototyping in the textile industry are high level garment simulations for overall wear comfort evaluation. These simulations heavily rely on dependable textile parameters and result in advantages that can be named as:

- faster progress from idea to final product,
- greater flexibility through digital prototyping as well as instantaneous feedback,
- fitting of multiple sizes and also fitting in motion (Fig. 1)
- and sampling of multiple fabric materials.

The accuracy of virtual garment simulations is largely dependent on the exact knowledge of the textile’s stress-strain profile (tensile & shear), bending stiffness, coefficient of friction and specimen surface weight [1]. A universal measuring unit was developed [3] which has the ability to quantify accurately all mentioned parameters (Fig. 2).

This contribution concentrates only on the single parameter coefficient of friction but as such is covered in great detail. These tribological parameter(s) of textiles from our experience and underpinned by practical experiments turned out to be the most demanding mechanical property. The difference between static and dynamic friction is crucial in the slipping of objects. In clothing for example, it is more comfortable to have an equal value for the static and dynamic
The larger the difference between those values, the more the clothes tend to stick to the body, which is often perceived as uncomfortable.

In a first attempt the friction properties had been examined using the friction unit of the universal loading machine, which observes a mass while sliding down a progressively inclined plane. The corresponding angle $\alpha$ of the tilted surface is used to calculate the related static coefficient of friction $\mu = \tan \alpha$. This assumption is justified as long as Coulomb’s law can be assumed valid for the tested materials.

$$F_R = \mu \cdot F_N$$

This impact results in a bulging action on the leading (downward facing) edge increasing as the tilt angle is gradually raised resulting in wrinkles of considerable size (see Fig. 3). The resulting force $F_R$ is then a combination out of shear and normal forces acting on the wrinkle. Also the texturized surfaces of two identical textiles as friction partners seem to act together as a kind of mechanical interlock, reminiscent of a velcro tape, which emphasizes the assumption, that influences other than adhesion are distorting the experiment. Additionally wrinkles are promoting stick-slip behaviour, which again leads to even more wrinkles.

To broadly avoid those unwanted deformations that ultimately could intermingle shear, normal forces and bending, the textile’s bottom layer can be stuck on a single-sided adhesive foil. This has been done for all results presented further. Doing so keeps elongation, wrinkle formation and stick-slip phenomena at a minimum level. Twelve repetitions of a single experiment have been performed using this assembly in order to characterize textile 1 (see Table 1). The variability of $\mu_{spec1}$ was still varying between 0.8 and 1.0.

These deviations from the mean of the results give reason to believe that Coulomb’s law might not be valid for a highly elastic material like textile. Or at least that the initially assumed linear model (Eq. 1) has to be extended to also consider the influence of further parameters, e.g. (area specific) contact force $p$ and relative velocity $v$

$$F_R = \mu (p, v) \cdot F_N.$$
Figure 3. Friction subassembly of the universal loading machine [3].

The experimental setup with the inclined-plane friction meter is therefore obviously unsuitable since the local pressure distribution can’t be assumed constant for changing tilt angles. This led us to devise a new arrangement presented here allowing the friction test to be performed at level angle.

2. Optimized arrangement of the friction unit

The optimized set up of the friction unit is shown in Fig. 4. It mainly consists of two orthogonally mounted load cells (products of HBM GmbH) and a specimen receptacle to fix to friction partner 1. The horizontally oriented load cell (measuring range 50 N) measures the resulting friction force $F_R$ and the vertically oriented one (measuring range 100 N) the normal force $F_N$ applied to by friction partner 2. From the highly time resolved ratio of $F_R(t)$ to $F_N(t)$, the friction coefficient $\mu(t)$ can be calculated.

The value of this ratio clearly is only representative for the friction coefficient if the two related forces are measured at the same instant in time $t$. Therefore they are measured simultaneously by two separate 24 bit analog to digital converters with associated analog front ends (Analog Devices’ AD7194). Their master clocks are synchronized via SPI communication after powering up the friction unit’s electronic. The sampling rate is 500 Hz and the result consists of measurands stable to approximately 21 bits (according to the data sheet). This fast sampling in combination with the accurate electronics enables a high quality analysis of friction properties.

The working principle of this set up makes it also possible to determine the breakaway force (needed to determine static friction’s $\mu_S$) as well as the acting friction force after the breakaway (needed to determine dynamic friction’s $\mu_D$) in a single experiment. It is easy to handle and delivers results very fast and accurately, because the only necessary operation is to pull friction partner 2 over the held fixed friction partner 1. All kinds of influences (relative velocity, contact force, direction of movement, skin hydration, etc.) can be varied by the user.

The most outstanding feature of this friction unit, however, is the possibility to use arbitrary materials for friction partner 2. This mighty tool for textile development allows to quantify the wearing comfort of garments by not only assessing the textile to textile friction but to an even greater extend, the friction between skin and e.g. the inner layer of any garment. To demonstrate the versatility of the system the experimental results presented in this paper are divided in the two main groups textile to textile friction and textile to skin friction.
3. Experiments and results

A comprehensive variation of textiles, a subset of which is presented in Table 1, has been tested (various material compositions of cotton, elastane, polyamide, polyester, virgin wool; smooth and bulky surfaces; striking and poor texturization; ones with predominant direction and ones without) to figure out the crucial parameters determining the friction behaviour. Note: A moving average filter of appropriate bandwidth has been used to largely suppress recorded oscillations stemming mostly from the dynamic properties of the mechanical setup and not so much from the friction partners.

| Nr. | Surface density | Composition | Surface condition |
|-----|-----------------|-------------|------------------|
| 1   | 165 g m$^{-2}$  | 55 % polyester, 45 % virgin wool | bulky, strong texturization |
| 2   | 120 g m$^{-2}$  | 100 % polyester | smooth, poor texturization |
| 3   | 165 g m$^{-2}$  | 100 % polyester | bulky fleece, no texturization |
| 4   | 200 g m$^{-2}$  | 93 % polyester, 7 % elastane | smooth, usual texturization |

3.1. Analysis of the textile to textile friction

This loading case is especially important in garments for sports with periodic repeated movements, e.g. in running, when the two pant legs rub against each other. Mainly the outer layers of the garments are affected in this process. The following properties were expected to seriously influence the friction coefficient in this experiment.

- orientation of yarns (warp vs. weft)
- texturizing of garments surface
- relative velocity between friction partners
- contact force between friction partners
- possible predominant direction of textile fibres

3.2. Results of textile to textile test case

A first conclusion is that rarely a noteworthy difference between static and dynamic friction can be observed. In most cases they are almost equal to each other as long as the essential experimental parameters (magnitude and orientation of acting contact force) stay constant. Only
bulky materials, such as textile 3, exhibit an exception. They tend to have a significant peak after the breakaway of friction partner 2, which can be seen in Figure 6. For all following diagrams the green graph stands for the friction coefficient, the blue one for the measured normal force and the red one for the measured friction force. Diagram 6 shows the highly time resolved study of a predominance in the textile’s direction. Just the high resolution in time enables the detection of breakaway peaks, which define the static friction coefficient $\mu_S$.

In this experiment friction partner 2 slides against friction partner 1 two times back and forth in warp direction while $F_N$ remains almost constant (note: $F_R$ and thus $\mu$ changed sign on the backward stroke. This sign was kept for clarity of presentation.). While the peaks of the forward direction reach just about $\mu_S \approx 1.25$ the ones of the backward direction go up to $\mu_S \approx 1.5$. As already mentioned, this bulky material shows variations of the static and dynamic friction. In the forth direction the dynamic friction $\mu_D$ reaches a value slightly lower than 1.0 and in backward direction slightly higher than 1.0. These results clearly exhibit the presence of a predominant direction for this bulky material.

![Figure 6. Influence of predominant direction.](image1)

![Figure 7. Dependency on contact force.](image2)

Textiles with a significant texturization of the surface (see magnified image of the yarns of textile 1 in Fig. 5), show a strong impact on the orientation of the yarns. This empirical observation confirms once more the assumption of the mechanical interlocking. Thus especially knitted and woven materials have to be characterized separately in warp and weft direction.

Contrary to expectations there is hardly seen any influence on the relative velocity between the friction partners. It is negligible and not necessary to be analysed in a Stibbeck-curve.

The most important influence comes with the contact force which is equal to the normal force $F_N$. It has comparably small consequences ($\approx 10\%$ of $\mu$) for materials with smooth surface conditions, such as textile 2. But especially for bulky materials (e.g. textile 1 and 3), it is crucial as Figure 7 emphasizes. Variations of $F_N$ lead to variations of the friction coefficient. While low forces lead to high friction ($\mu_{\text{max}} \approx 0.9$), do high forces lead to low friction ($\mu_{\text{min}} \approx 0.5$).

3.3. Analysis of the textile to skin friction

This loading case is important for each garment’s inner layer that directly gets in contact to the user’s skin. All dependencies of the textile to textile case have to be considered here as
well. Additionally the factors skin hydration as well as body region were expected to seriously influence the friction coefficient in these experiments. These attributes have been examined in [4] as well, where the goal was a generalized examination of human skin friction. The conclusion of [4] resulted in the opinion, that the friction behaviour of in-vivo human skin is too complex to be replaced by any representative material in the research of textile to skin friction. Nonetheless it should be mentioned, that the synthetic skin substitute HUMSkin [6] achieves great results in the field of cosmetic development and should be considered for future friction tests.

3.4. Results of textile to skin test case

The main dependencies in these experiments turned out again to be the contact force and additionally the skin hydration. The consequences are also limited for smooth surfaces but turned out to be significant for bulky ones. Using textile 2, Figure 8 shows the friction coefficient remains largely constant even if the variation of the normal force is significant.

The skin hydration and body region also have a major influence on the friction between the garment and the user’s skin. Figure 9 shows the variation of the friction coefficient dependent on the skin hydration. The red curve $\mu_1$ was recorded with 27 % (upper arm), the blue one $\mu_2$ with 45 % (palm of the hand) and the green one $\mu_3$ with 99 % skin hydration (palm of the hand). The skin hydration level was measured with the device Ckeyin SK-IV which uses the so-called bioelectric impedance analysis.

![Figure 8](image1.png)  
**Figure 8.** No dependency on contact force.

![Figure 9](image2.png)  
**Figure 9.** Dependency on skin hydration.

4. Acknowledgement

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5. References

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