A Contribution to the Measurement of Skin to Textile Friction

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***Abstract*—In this work, we detail the problems encountered and recommended associated solutions in determinig the tribological properties of fabric frictioning vis-à-vis human skin under various conditions like dry skin, conditioned skin, and sweaty skin, to name just a few. Furthermore, we report on the necessary measurement setup to reliably determine the non-linear frictional behaviour of different fabric being the friction partner to like and other types of fabric, which are either stretched and thus mechanically loaded or otherwise untensioned and possibly hanging loose. Those cases are encountered in textiles worn under different physical activities like various sport activities or might play an important role in textile-based medical devices like surgical stockings, band–aids, etc. By analyzing various influences it can be shown that Coulomb's law for rigid body friction must be extended to also include the dependency on parameters such as yarn orientation, skin hydration, contact force and fabric pre–stretch. The developed system is easy to use and measures reliably and reproducibly both dynamic and static friction for most typically encountered friction partners.**

Keywords*–*non-coulomb friction; coefficient of friction; in–vivo human skin friction; tribological behaviour of human skin; friction measurement.

I. INTRODUCTION

Lately, there has been a dramatic increase in interest in rapid prototyping in the textile industry, which is relying on high performance garment simulations with the overall goal to increase wear comfort in particular in sportswear. Clearly, meaningful simulations heavily depend on reliable textile parameters and associated friction models and result in design advantages that can be named as:

- faster progress from idea to final product,
- greater flexibility by instantaneous feedback,
- fitting in motion (results see Figure 1 for a tennis player's action as input for a garment simulation software),
- and comparison of fabric materials.

The exactness of garment simulations is dependent on the knowledge of the textile's stress-strain profile (tensile & shear), its bending stiffness, its coefficient of friction and specimen surface weight [1] [2]. A universal measuring machine to address and measure all those parameters (except surface weight) was developed and tested successfully [3] for a colleague (mentioned in the acknowledgement) who also provided the garment simulation results from previous work of her which is which is depicted in Figure 1.

Figure 1. Garment simulation to result in strain values (colorcoded) with permission from [1].

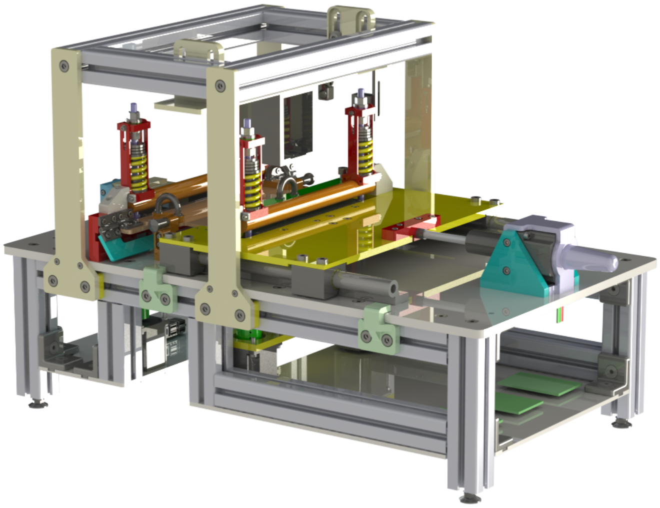

Figure 2. Photo of a textile characterization system [3].

The paper is structured as follows, in Section II the peculiarities of textile friction partners are stressed over those showing solid body friction, Section III details the chosen sensors and their arrangement to allow even human skin as friction partner in dynamic friction tests, Section IV describes experiments to characterize textiles on their friction behaviour for both skin and other textiles as friction partners and discusses the measurement results obtained, and Section V concludes the paper.

II. TRIBOLOGICAL DESCRIPTION OF TEXTILES

In the regime of Coulomb type friction between two dry solid bodies the maximum tangential force can be defined as $F_t = \mu F_N$, where F_N is the normal force acting on the interface perpendicularly to two parallel flat surfaces of the friction partners and F_t is the maximum sustainable friction force. The coefficient of friction μ is a dimensionless, in this particular case, scalar constant that describes the maximum friction force below which static friction occurs. Exceeding that tangential force will lead to kinetic friction and the partners will slide against each other effectively generating heat. The coefficient of friction is dependent on the materials of the frictioning partners, the possible deformation of one or both partners, and surface roughness, both seen at the microscopic level and is conveyed by the chemical bonding between atoms in the bulk materials. For static friction of solid bodies, the following equation is to hold: $-\mu F_N < F_R < +\mu F_N$. For textiles that can presumably be stretched, however, and thus do not act as solid bodies this friction model seems to be oversimplified. For resilient materials, areas of the friction partners might experience higher than average normal forces whereas other areas might in turn see even bulging of the textile, specifically where compressive tangential forces might act upon the textile resulting in local wrinkling. Clearly, this bulging might be located at areas where the textile formed into a garment experiences belt-type friction at wrapped around locations, particularly at the knees or elbow areas.

Moreover, if these textiles are to absorb sweat during sports activities the model of dry-friction might not be able to describe properly the friction behaviour under these conditions. Slightly damp garments might on the other hand be only described by a deficient fluid-type friction, since in true fluid friction a fluid film effectively separates the two — most of the time — solid surfaces thus decreasing the friction forces. As it is common knowledge damp or almost wet garments tend to even stick better to the skin (and can be taken off harder) than still dry garments. To complicate things even further skin of different body parts also tend to behave differently friction–wise and need to be studied case by case using an easy to use equipment.

From the above presented facts, it seems clear that the measurement of tribological parameters of skin to textile friction is an involved problem and requires a careful planning of the experiments and also a very flexible kind of measurement equipment to cover the wide variety of friction partners under different pre–loading conditions and also allows for skin at different body parts to be used as friction partner. In this contribution, we present a system that is able to allow the analysis and measurement of tribological parameters using even human skin as friction partner.

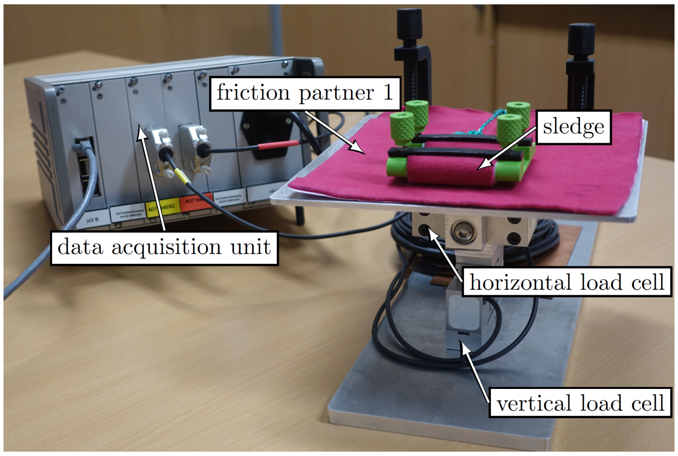

Figure 3. View of the measurement system exhibiting the cross–mounted load cells ($F_{\max} = 100$ N for the vertically oriented and $F_{\max} = 50$ N for the horizontally oriented cell).

While analyzing results obtained for the coefficient of friction from the universal textile measurement machine, which still assumed that a single figure of merit might characterize all of the tribological behaviour of such complex friction partners like garment and dry, or conditioned or hydrated skin it became apparent that a more detailed study has to be undertaken. This contribution extends considerably to and concentrates only on the single parameter coefficient of friction but as such it is covered in greater detail as given in [2]. The 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 as equally crucial in the slipping of objects (garment vs. skin) as is the consideration of the compliance of textile under mechanical load in the direction of the yarn if stretched under sports action and also if the more complicated belt–friction case is considered if the friction partner is wrapped around a knee or an elbow for example. In clothing simulation software for example, it is typical to have only a single value to cover both the static and dynamic effects due to friction [4]. So, the results can not cover the known tendency, caused by larger differences between static and dynamic friction, of clothes to stick to the body for a flexing action and loosen for a stretching action, which is often perceived as rather uncomfortable.

In Figure 2 a textile testing maschine developed in a former project by the authors is depicted. It is able to measure in a single unit stress–strain behaviour, bending stiffness, and coefficient of friction (here still assuming the simple Coulomb's model). While analyzing all the problems encountered operating this machine it was decided to single out the friction measuremen part of the fabric characerization and devise a novel set–up, which is depicted in Figure 3.

III. OPTIMIZED ARRANGEMENT OF THE FRICTION UNIT

This optimized set up of the friction-only unit is shown in Figure 3. It mainly consists of two orthogonally mounted load cells (products of HBM GmbH, Germany) and a specimen receptacle to fix to friction partner 1.

The horizontally oriented load cell (measuring range $50\,\mathrm{N}$)

measures the resulting friction force F_R and the vertically oriented one (measuring range $100\,\mathrm{N}$) the normal force F_N applied to by friction partner 2. From the highly time resolved aquired data (sampling time 2 ms) the 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 $500\,\mathrm{Hz}$ 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 μ_S) as well as the acting friction force after the breakaway (needed to determine dynamic friction's μ_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.

A novel version that incorporates three orthogonally acting load cells is currently under construction and should then be able to determine the coefficient of friction for the dynamic case as a tensor. The idea of which is commonly seen if two textiles are rubbed against each other using thumb and forefinger on a circular motion *trajectory* and experiencing a preferential direction leading to a non–circular reaction. Furthermore, the next version of the system will be so compact in design as to also allow for the second partner (the fabric) to be fixed to a (then non–planar) template mimicking the counterpart of a knee or an elbow with the actual like human part's skin as friction partner for the test. Thus, the results obtained from such a unit will be very close to the true tribologic behaviour of garment.

To demonstrate the versatility of the current system the experimental results presented in this paper are divided in the two main groups *textile to textile friction* and *textile to skin friction*.

IV. EXPERIMENTS AND RESULTS

A selection of textiles (44 in all) were tested to get a feeling in the development phase about the necessary ranges of the forces involved. As was expected, the friction forces covered a very wide range from very little friction of a thin barely loaded silk scarf vis-à-vis silk, to structured wool vis-à-vis almost pressed against fatty skin. A subset of the materials are presented in Table 1, to get a feeling about the variety. The tested specimen were material compositions of cotton, elastane, polyamide, polyester, virgin wool; smooth and bulky surfaces; striking and poor texturization; ones with predominant direction and ones without. While testing it turned out that the high frequency oscillations initially seen in a dramatic way in all the time domain signals acquired (F_N and F_R) largely were due to the dynamic behavior of the measurement system itself, which exhibits sufficient stiffness to be excited to oscillations beyond approximately 70 Hz for the horizontal and approximately 50 Hz for the vertical load cell. A striking example of these deteriorating oscillations is given in Figure 5, so appropriate measures were needed to suppress, thus a moving average filter of appropriate bandwidth ($<$ 30 Hz) has been used to do so to only record the dynamic forces induced by the interaction of the friction partners.

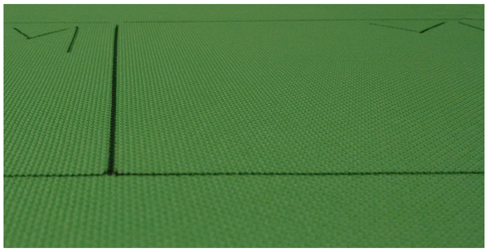

Figure 4. Zoomed in view of the structure of a textile. The width is approximately 100 mm.

TABLE I. DESCRIPTION OF THE MATERIALS UNDER TEST

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

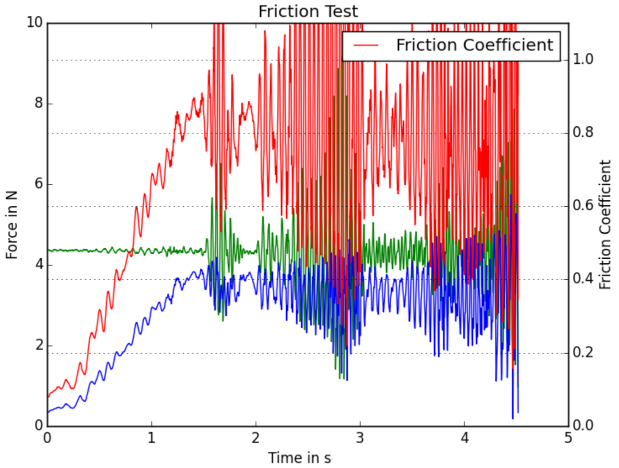

Figure 5. Initial test results exhibiting significant parasitic oscillations.

A. *Analysis of the textile to textile friction*

This loading case is especially important in garments for sportswear that is subject to periodic repeated movements, e.g., in running, when the two pant legs rub against each other during each stroke. 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) of the frictioning partners
- texturizing of garments outer layer
- relative velocity of the friction partners
- contact force between them
- possible predominant orientation of textile fibres

B. Results of textile to textile test case

A first conclusion drawn from the experiments is that rarely a noteworthy difference between static and dynamic friction can be observed. In almost all cases both are almost equal as long as the experimental parameters (magnitude and orientation of the acting contact force) remains constant. Only bulky materials, such as textile 3, exhibit an exception. They tend to have a significant friction force overshoot preceeding the point of breakaway from 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 (always opposing the possible motion). Figure 6 shows the highly time resolved value (1000 samples recorded per second) of the friction force opposing the motion, dependent on the textile's orientation. Just this high resolution in time enables the detection of breakaway peaks, which define according to Coulomb's law the static coefficient of friction μ_S.

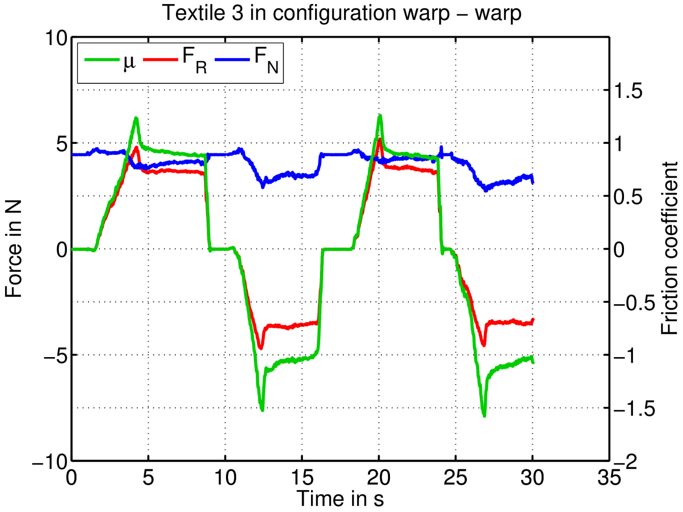

Figure 6. Significant overshoot of friction force preceeding the point in time when the kinetic friction sets in (at appox. 4 s, 12 s, 20 s, and 27 s in time).

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 so mathematically also μ changed sign on the backward stroke. This sign was only 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 μ_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 material.

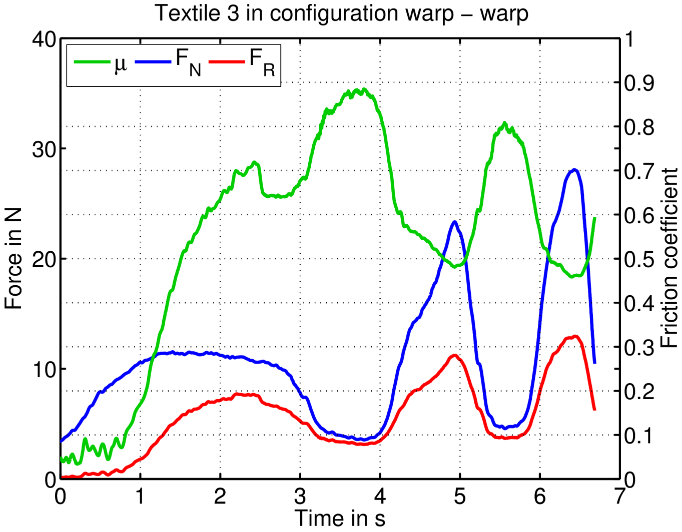

Figure 7. An unexpected dependency on the normal force can be seen in structured materials exhibiting significant texturization. This behaviour might hint on mechanical interlocking of structures.

Textiles with a significant texturization of the surface (see magnified image of the yarns of a textile in Figure 4), exhibit a rather pronounced impact on the orientation of the yarns with respect to the intended motion. This empirical observation confirms once more the assumption of a possible 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 thus not necessary to be analysed in a Stribeck-type curve [5].

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 μ) 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 ($\mu_{\max} \approx 0.9$), do high forces lead to low friction ($\mu_{\min} \approx 0.5$).

C. 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

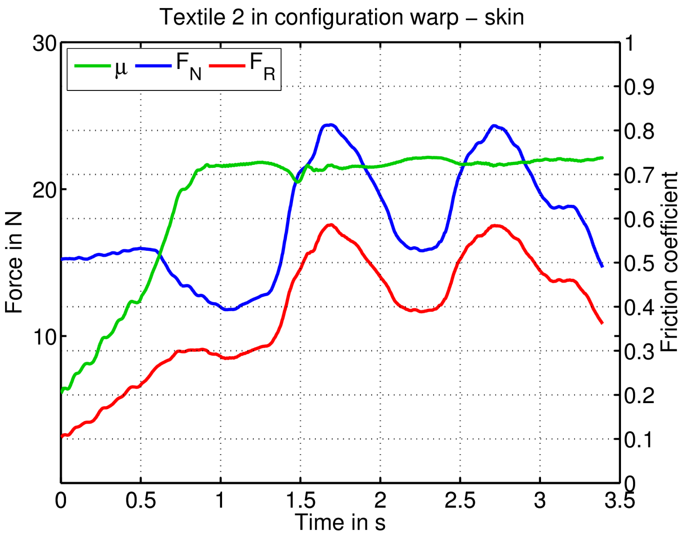

Figure 8. A textile to skin friction experiment (with constant, though undetermined skin hydration) exhibited very little dependency on the applied normal, contact force.

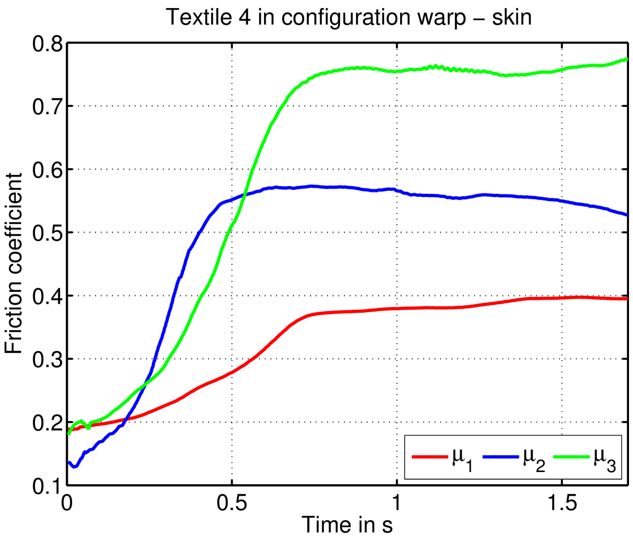

Figure 9. Tribologic significance of textile to skin friction dependent on skin hydration. (Red) skin of upper arm, hydration 27 %, (Blue) palmar side of hand, hydration 45 %, (Green) palm of (sweating) hand, hydration 99 %.

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.

D. 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. In analyzing textile 2 the results showed the friction coefficient remains largely constant even if the variation of the normal force is significant (see Figure 8). Skin hydration and its location on the body also have a major influence on the apparent friction between the garment and the user's skin. Figure 9 shows the variation of the friction coefficient dependent on the skin hydration. The skin hydration was determined with a device used by beauticians and those results can not be really be considered measured quantities, although the results in Figure 9 seem to indicate some effects with the correct trend.

The red curve μ_1 was recorded at the dorsal upper arm with 27 % hydration, the blue one μ_2 was recorded with the palmar side of the hand with 45 % hydration and the green one μ_3 was recorded also with the palm of the hand though sweating with 99 % skin hydration. The skin hydration level was determined as indicated above using a device called *Ckeyin SK-IV*, which uses the so-called bioelectric impedance analysis to indicate skin hydration.

V. CONCLUSION

The assumption that the tribology of textiles in both textile to textile or textile to skin friction cases can be described accurately by a single parameter μ_R was shown to be clearly wrong. There are types of fabric that show a significant dependency on the acting normal force and other types seem to show no dependency at all. The most interesting fact exhibited for the cases of skin to fabric friction is the clearly shown dependency on skin conditions like hydration and location on the body of the considered skin as friction partner. These facts lead to the conclusion that garment simulation software will have to incorpoate a much more involved tribological model for any pairing of friction partners relevant to the garment industry.

ACKNOWLEDGMENT

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