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Abstract	The study of the tribological properties of the skin is a very important research field for medical investigation, development of dermatological products and the analysis of the interactions between textile products and the skin. To obtain these properties it is necessary to perform tests using tribological equipments which can simulate the conditions to obtain reliable values that will allow the measurement of skin wrinkling. The skin aggressions are usually analyzed using special equipments, known as tribometers, that enable the performance of the tribological characterization of a pair of materials, in order to obtain parameters such as friction coefficient and wear; for this purpose, the control of test variables, such as normal applied load, displacement speed, environmental conditions and other relevant circumstances which influence the interaction of surfaces in contact is required. The most important objective is the evaluation of a concept commonly known as touch, difficult to define and measure (which is related to the quantification of the level of comfort provided by the contact with the skin), with the requirement of studying soft materials, namely the skin. For that purpose it became necessary to design and manufacture a tribological equipment capable of responding to the demands of the required tests.
Keywords (separated by '-')	Mechanical design - Tribometer - Instrumentation and control - 3D modelling

Study, Design, Development and Construction of a Linear Tribometer for Testing Human Skin

Eurico Seabra, Luís F. Silva, José Martins and Mário Lima

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Keywords Mechanical design · Tribometer · Instrumentation and control · 3D modelling

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1 Introduction

The human skin is the largest organ of the human body, enabling a vital defense mechanism, by forming a barrier between the interior and the external environment. It not only contains but also supports and protects the internal organs of the body to a certain degree of abrasion, wear and bruising, also allowing a considerable mobility of the body (Elder et al. 2001).

The human skin is exposed to various types of attacks that can be mechanical, chemical or microbiological, promoting many problems to the skin. Many of these aggressions are caused by the interactions between the skin and textile products due to friction, by the application of creams and by the use of different medical devices, among others. These attacks tend to modify the properties of the skin, such as elasticity, roughness and moisture (Leonardi et al. 2002).

Therefore it is of upmost importance to study the skin interaction with other elements in order to minimize cases of skin damage, which often cause irritation and pain, or simply to improve comfort and quality of life. Tribometers are often used to analyze and better understand these phenomena. With this equipment it is possible to tribologically characterize the materials in contact and to obtain important parameters, such as coefficient of friction and wear. Therefore, the need to control the test variables (normal applied load, displacement speed, environmental conditions, lubrication, and others that are relevant and capable of influencing the interaction between the surfaces) is important in this study.

This project was directed to the study of flexible and deformable materials, in particular those that are in direct contact with the human skin, as well as to the design and development of a tribological equipment capable of meeting the requirements for these tests.

Through these tests it was possible to measure the coefficient of friction between the two materials in contact, the rubbing probe and the material sample. To accomplish the main goal, a certain number of specifications were established. Different grabbing sample systems have been studied, as well as displacement systems, control of the testing speed and probe types. Other essential conditions were considered to allow the use of an existing equipment in the Mechanical Engineering Department of the University of Minho.

Firstly, a market analysis was performed for the various types of existing tribometers and the advantages and disadvantages for this application were identified. On a second stage, the objectives tree method and the function analysis method were used. According to the objectives to be achieved and the specifications to be met, the design and analysis of various alternative solutions were undertaken to determine the best solution for the testing equipment, in a simpler, practical, economical and feasible way.

Three-dimensional representations of all the components were carried out, as well as the overall assembly of the designed tribometer, using the AutoCAD® and the SolidWorks® software packages (Planchard 2014) for their mechanical design and simulation.

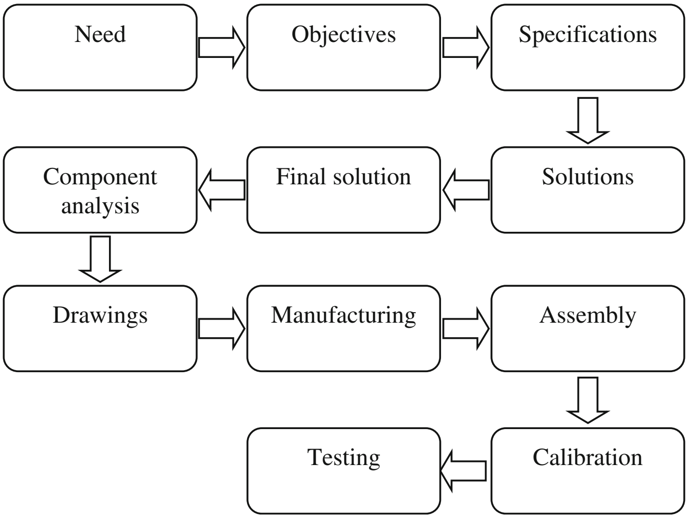


Fig. 1 Development stages of the project

A final prototype was built and assembled. The probe's displacement and velocity, as well as the potentiometric ruler, the load cell and the laser sensor for measuring the roughness of the testing sample were calibrated.

Finally, systematic tests were carried out on different samples at various speeds to demonstrate the tribometer's working principle and its feasibility.

Figure 1 shows, schematically, the different performed stages for the development of this equipment:

2 Tribometer Types

With the objective of developing a capable testing equipment, an analysis of several different types of devices available in the market was carried out.

In the field of tribology of deformable materials, various methods for friction testing are employed; the most used are the linear method and the rotary method. The following sections will be addressed to the presentation of these two methods.

2.1 Linear Method

The linear method is based on slipping a probe on a sample, or vice versa, straight and hence generating a frictional force. The friction coefficient is obtained by dividing the friction force by the normal force applied to the sample and probe set;

the static coefficient is obtained using the force required to initiate movement, while the dynamic coefficient is obtained using the frictional force required to maintain movement.

The method used in the tribometer is linear and has a pin type probe. Using this method, the sample is axially loaded by the probe and an alternate linear motion is forced between the two surfaces in contact (i.e. between the probe and the testing sample). In consequence, a frictional force opposing the displacement of the probe is developed, as shown in Fig. 2.

The friction coefficient μ is then obtained by dividing the friction force ($F_{friction}$) by the normal applied force N through the following Amontons' law of friction:

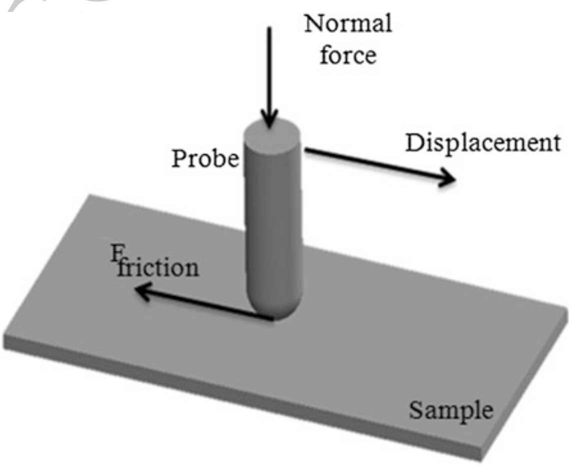
$$\mu = \frac{F_{friction}}{N} \tag{1}$$

Figure 3 represents the main components of a linear tribometer for the measurement of the friction coefficient:

Another type of study within the linear method is to obtain the friction coefficient through the resulting friction force of dragging strips on samples or even on the forearm of human volunteers.

In the study of different contact materials with the human skin, there is an equipment that has the ability to measure different materials properties (with greater focus on textile materials) using a set of multiple devices, being the most representative the so called Kawabata Evaluation System (or KES) (Kawabata and Niwa 1989; Wu et al. 2003); this system is presented in Fig. 4.

Fig. 2 Working principle of a tribometer



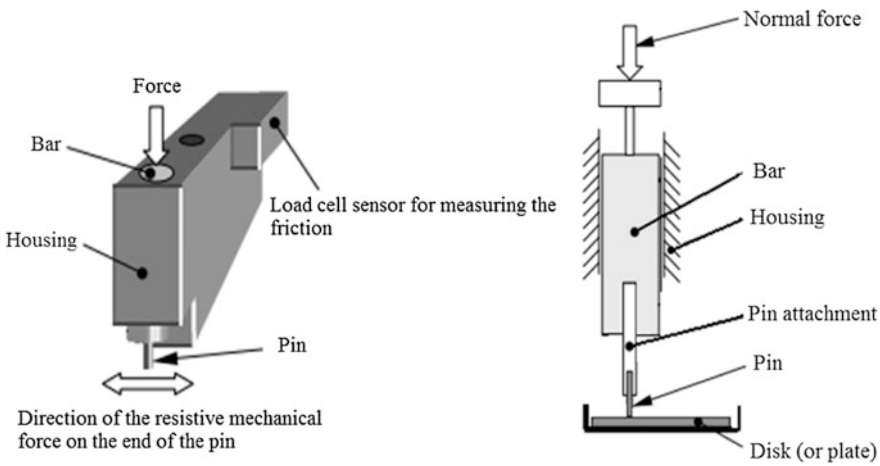


Fig. 3 Example of the measurement of the coefficient of friction in a linear tribometer

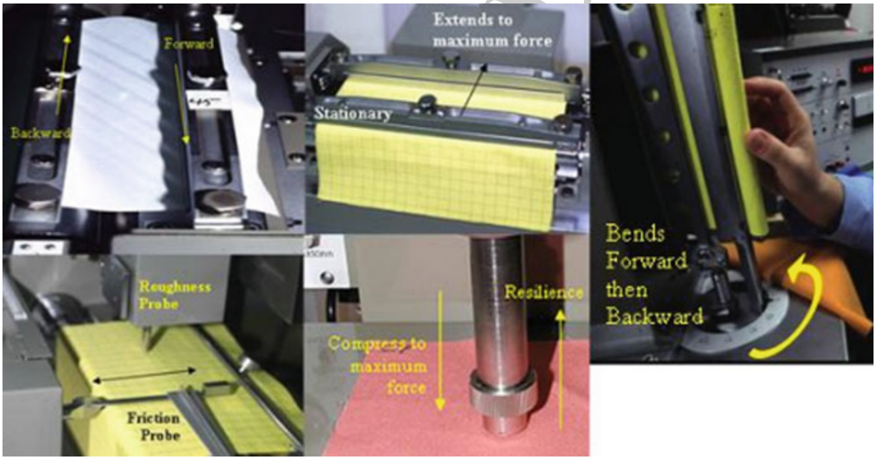


Fig. 4 The kawabata evaluation system (or KES) (Kawabata and Niwa 1989)

The KES is made up of four different equipments, which enables the following types of tests:

- Tensile;
- Compression;
- Bending;
- Friction;
- Roughness.

This testing equipment is one of the most complete in the market, however it is not widely used in industry due to its high cost.

2.2 Rotary Method

The rotary method uses a ring-shaped contact body (with an outside diameter D and an inside diameter d), which rotates around its axis and wherein a contact force P is applied on the sample. Its operation principle is schematically shown in Fig. 5.

The first development has led to the design of a friction test rig whose operating principle is based on a dry clutch disc, where a planar body with an annular configuration (as shown in Fig. 6) is dragged onto another flat surface, rotating around an axis perpendicular to the contact plan, under the action of a given normal force (P) resulting in an uniform distributed contact pressure. This is the principle used by FRICTORQ, which is a laboratory equipment designed to measure the coefficient of friction in fabrics and other planar flexible surfaces. It is made up by a high precision torque sensor (with a data acquisition system), a DC motor (with a gear reducer and a timing belt to drive the support of the fabric sample) and by a software application to control the whole system. The friction coefficient is then proportional to the level of torque being measured by the torque sensor.

The upper body is also designed to be a "standard" body, ensuring a certain contact pressure and linear velocity (Lima et al. 2005, 2007; Macedo et al. 2012). This upper test body is built to accommodate different types of surfaces, as depicted in Fig. 7.

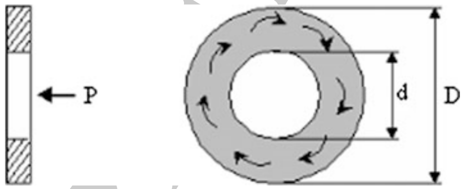


Fig. 5 A ring-shaped contact body used on a rotary method

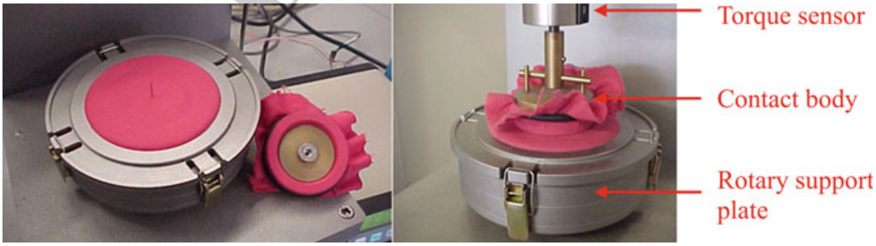


Fig. 6 The FRICTORQ equipment on a fabric-to-fabric set up

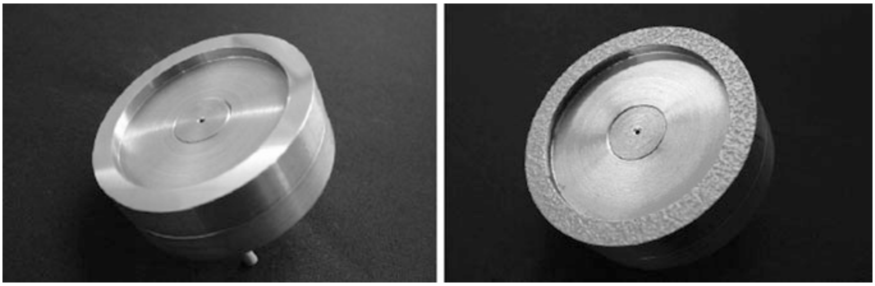


Fig. 7 A detail of the smooth (*left image*) or textured (*right image*) metallic bodies used as "standard" testing bodies

3 Design and Development of the Linear Tribometer

As mentioned, different phases were undertaken for the design and development of a linear tribometer: the design problem was clarified, an objectives tree was established, the specifications were decided and the best solution was chosen taking into account all the established requirements.

3.1 The Objectives Tree

After market research and to further clarify the various possibilities to consider and implement for each one of the different equipment systems, a diagrammatic objectives/functions tree was drawn, as presented in Fig. 8, where each function is an objective that may be achieved by different means (sub-objectives).

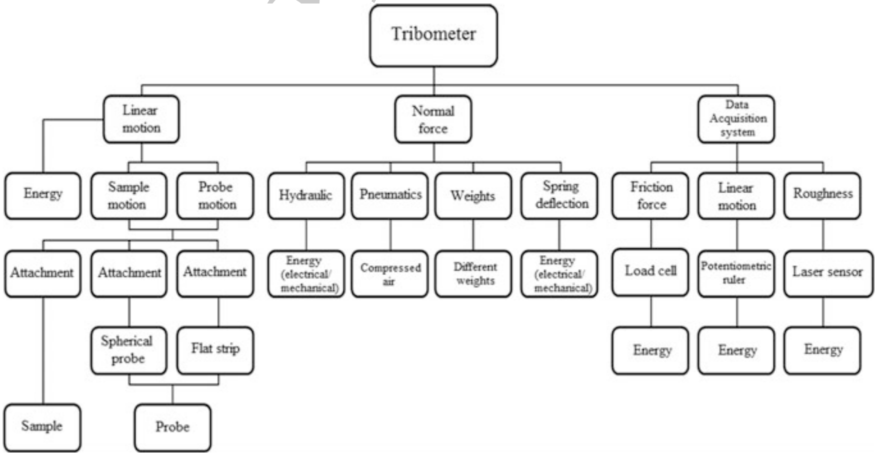


Fig. 8 A functions tree for a linear tribometer

Table 1 Objectives/specifications for the design and development of the linear tribometer

Description	Item
Type of tests	Measurement of the friction coefficient and of the profile of roughness
Normal force	Varying from the probe's weight to 2 kg; by gravity
Motion type	Alternative linear motion
Displacement	Varying from a minimum of 5 mm to a maximum of 280 mm
Linear velocity	Varying from 1 to 15 mm/min
Friction force and roughness measurement	Tension and compression load cell (friction force) and laser sensor (roughness)
Probe's geometry	Spherical (contact) end

3.2 Specifications

A series of initial objectives and specifications were addressed to this design. These defined which type of tribometer, sample, probe and applied forces should be used, as well as other working parameters—see Table 1.

3.3 Tests

As mentioned earlier, tribometers are capable of measuring the frictional force between two surfaces. For this particular linear tribometer it is also needed that the testing equipment is also capable of measuring surface roughness of the sample that is being tested using a laser sensor.

3.3.1 Normal Force

For the normal force, the manual application of weights was chosen mainly due to its simplicity and compactness, and because it was the most cost-effective solution. One of the main drawbacks of this loading system is the need for different calibrated weights to apply different loads, which initially involves a lower range of possible loads. This solution uses a thin glass tube (a typical lab test tube); first, the probe with the desired geometry and material is inserted, and then the successive weights to achieve the desired normal force are also added.

3.3.2 Linear Motion Between the Sample and the Probe

For this purpose a motorized linear slide table by FESTO was used with the reference TLH 300. Its movement is carried out using a DC motor and the maximum displacement is 280 mm.

3.3.3 Displacement Amplitude

The used linear slide table has two position adjustable end stop sensors that enable a working testing displacement between 5 and 280 mm.

3.3.4 Linear Velocities and Direction of Motion

The linear movement of the slide table is accomplished by means of a DC motor coupled to a 3 mm pitch power screw, allowing the change of the testing velocity and direction of the linear movement of the table, respectively, by modifying and inverting the voltage applied to the DC motor.

3.3.5 Friction Force Measurement and Surface Roughness

The friction coefficient is obtained by dividing the friction force by the normal force. The normal force is previously known, being necessary to determine the frictional force during the tests. This is measured by a load cell, reference WMCP 1000G (from Interface), being capable of measuring a maximum of (tensile and compression forces of) 1 kg_f. To measure the roughness profile/wrinkle of the sample, a laser triangulation sensor from Micro-Epsilon, optoNCDT 1302 model, was selected.

3.3.6 Probe's Geometry

The probe is the component where the normal force is applied. It is also the component that will come into direct contact with the sample. Its geometry is important in that contact so it cannot generate any other forces in directions not perpendicular to the normal force, which will influence the correct measurement of the frictional force by the load cell.

3.4 Design of the Components

The purpose of this section is the design of the main components of the linear tribometer, namely the structure and attachment of the load cell and the laser sensor. The design of the mentioned components, to accomplish their functions without collapsing and without deforming or vibrating excessively, was carried out within certain limits, which are defined by technical standards.

Therefore, the main steps of this design phase were, after the creation of the structural scheme, the definition of the forces acting on the structure and the identification of its constraints, to subsequently determine the forces and deflections.

3.4.1 Tribometer Structure

To design of the tribometer's (support) table, the actual weight of the tribometer table was applied which is approximately 8 kg_f. To perform the test, the forces were applied on top of the structure, as well as on the locations where the bottom of the structure is attached. Figure 9 shows the results of the numerical simulations carried out using finite elements.

Considering a finite element mesh of 4 mm, the maximum results obtained for deformation and stress were, respectively, 0.01 mm and 5.83 MPa. The deformation is within the limits considered and since the forces are very small, the maximum obtained stress is much smaller than the lower yield strength of all the used materials.

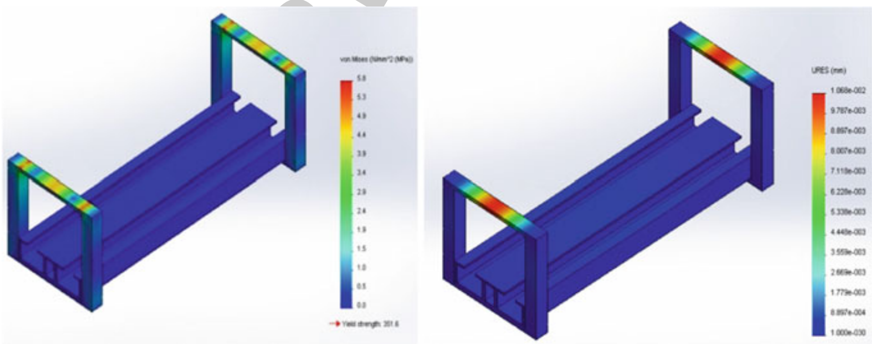


Fig. 9 Results obtained in a simulation with a force of 78.5 N

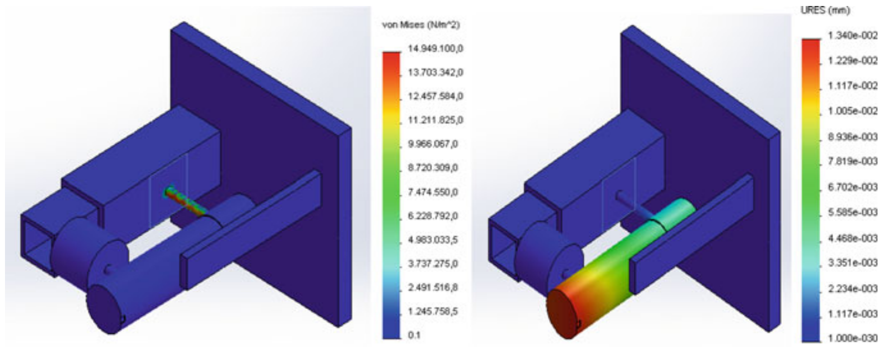


Fig. 10 Results obtained in the simulation with the load cell attachment

3.4.2 Design of the Attachment System for the Load Cell, Probe and Laser Sensor

This system is responsible for the attachment of the electronic components, such as the load cell (which will measure the frictional force generated by sliding of the probe over the sample at a given normal force). This movement will generate tensions in this support base. Considering the same finite element mesh of 4 mm, the maximum deformation and stress were, respectively, 0.013 mm and 15 MPa. The deformation is within the limits imposed and, again, since the forces are very small, the maximum obtained stress is much smaller than the yield strength of the used material. Figure 10 shows the obtained results.

3.5 Construction of the Tribometer Prototype

After the conclusion of the conceptual, preliminary and detailed design phases, the construction and assembly of the tribometer prototype was undertaken. Figure 11 shows the testing apparatus of the built linear tribometer, as well as the entire implemented command and control systems (hardware and software). After the conclusion of this phase, a preliminary test validation of the tribometer was performed.

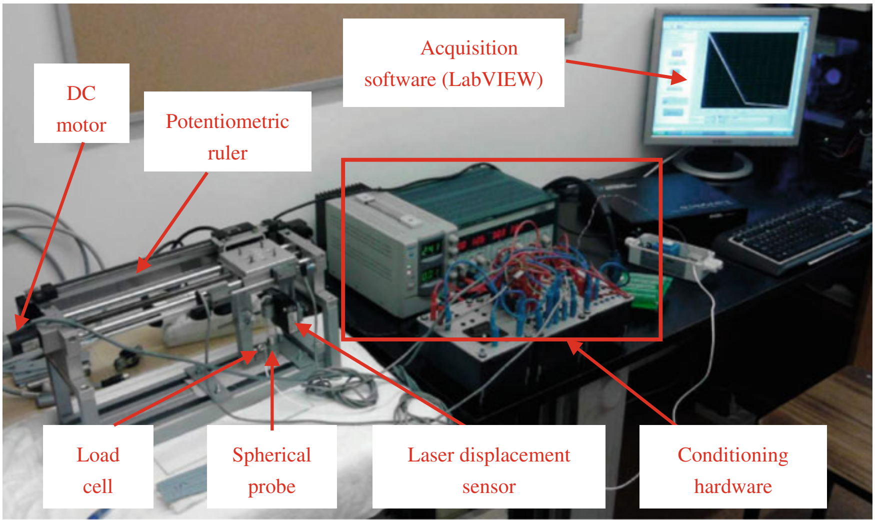


Fig. 11 Overall view of the developed linear tribometer

4 Validation Tests

After all the phases previously described and after the calibration of the different components to make this a reliable tribometer, validation tests were performed to the testing equipment (values of the coefficients of friction) using six samples of textile fabrics.

To prove that the linear tribometer was providing reliable data, it was decided to compare the obtained results using the set up parameters and criteria (in terms of velocity, displacement, sample type and normal forces) to carry out tests with the same conditions on a different tribometer, namely, the FRICTORQ testing equipment previously mentioned.

Due to the fact that FRICTORQ uses the rotary method and the proposed design uses a linear one, the linear velocity in the contact had to be determined using the angular velocity of the FRICTORQ; a tachometer was used to measure 0.7 rpm, and knowing that the average radius of the test probe body (see again Fig. 7) is 21 mm, the equivalent linear speed is 92.4 mm/min, i.e. the velocity to be applied to the linear tribometer. Another important parameter was the distance traveled by the probe: the distance should be similar. The FRICTORQ was considered as reference, because the linear tribometer is the only one capable to adjust the distance travelled by the testing probe. Then, the distance travelled by the probe was determined, which is the perimeter corresponding to the FRICTORQ mean contact circumference (131.8 mm). A probe with a mass of 25 g was used in the linear tribometer, to replicate the same conditions as in the FRICTORQ.

Figure 12 highlights the samples chosen to determine the friction coefficient of six different textile fabrics, each of which was subjected to two tests corresponding to a total of twelve tests on each of the two tribometers (in a total of twenty-four tests).

Initially the tests were carried out on the FRICTORQ, due to its inability to control variables, such as, velocity, displacement and height of the sample relative to the linear tribometer. After their observation and using similar test conditions (in terms of samples, velocity, displacement and normal force) it was possible to carry out the same tests in the linear tribometer.

Figure 13 shows the main results for the obtained coefficient of friction obtained with both tribometers. Analyzing the results, it can be seen that in both tribometers the coefficient of friction average values are real close: the biggest difference was observed in sample 2 (0.05) and equal results have been found for sample 5. In

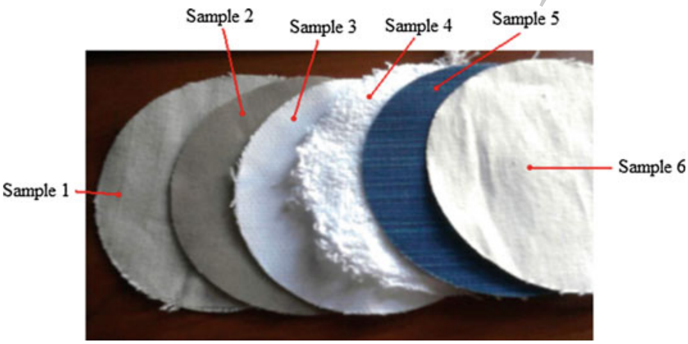


Fig. 12 Six different textile fabrics tested on the linear tribometer

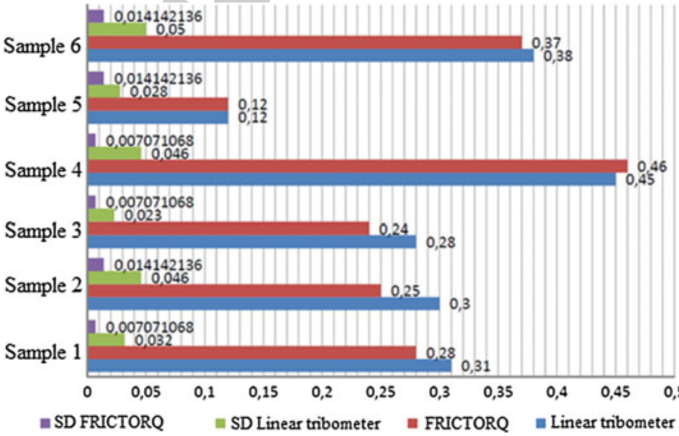


Fig. 13 Results obtained for the coefficients of friction of the six textile fabrics tested

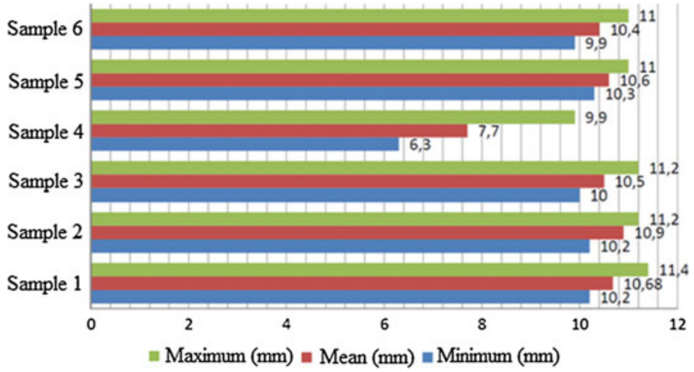


Fig. 14 Results obtained for the roughness of the six textile fabrics tested

terms of standard deviation (SD), it can be noticed that there are some differences between the results obtained with the two tribometers: this can be explained by the differences between the data acquisition systems (different acquisition rates). Although in both tribometers the SD is low, the biggest value was 0.05 in sample 6, with the linear tribometer, and 0.01 in samples 2, 5 and 6 with the FRICTORQ.

In order to determine if there is a correlation between the results obtained for the friction coefficients (see Fig. 13) and the roughness of the samples, Fig. 14 shows the roughness values measured by the laser sensor attached to the linear tribometer.

Sample 4 is the one that shows a more evident correlation, because it is the sample with the higher coefficient of friction, and with the greater surface roughness (higher range of values). Sample 5 is the sample that has a lower coefficient of friction, as well as a lower roughness (range of values). The remaining samples (1, 2, 3 and 6) are very similar, in terms of coefficient of friction as well as in terms of roughness.

Thus it can be concluded for the tested fabrics that there is a relationship between surface roughness and the coefficient of friction of a material, i.e. the greater the range of roughness values, the higher is the coefficient of friction of such material.

5 Conclusions

Regarding the design and development of a new linear tribometer for testing the human skin, it was possible to create a suitable, versatile and feasible equipment that meets all the required specifications.

The new linear tribometer herein proposed was validated comparing its results for the coefficient of friction with the ones measured under similar conditions in an existing tribometer. The results suggest and demonstrate the reliability and accuracy of the data obtained by the developed linear tribometer.

Future work will be directed to the optimization of the acquisition and control systems of the linear tribometer and more validation tests will be undertaken using other types of materials, in particular silicone laminates that simulate human skin.

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