The tribological behaviour of skin equivalent materials and ex-vivo human skin during sliding contact with artificial turf

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ABSTRACT

The use of synthetic materials for outdoor and indoor sport fields has increased over the last decades. Artificial turfs, commonly used on football fields, are basically infilled with recycled crumb rubber derived from old tires, the main of which are NBR (acrylonitrile butadiene rubber) and SBR (styrene-butadiene rubber) with fibers usually made of Polyethylene (PE) or Nylon. The use of these polymers for artificial turf designing purposes has caused controversy to whether their impact in human health, especially in skin abrasions during players sliding on the artificial turf. We have studied the tribological performance of different artificial human skin and real human skin against NBR, PE and Nylon 6.6 at different environmental conditions: normal conditions (25 ˚C and 50% of relative humidity) and high humidity conditions (37 ˚C and 80% of relative humidity) and forces of 2 and 4 N to achieve the association between friction and skin damage. The applied forces correspond to a range of pressures of 121 to 175 kPa and the experiments were conducted at 50 mm/s. The friction coefficient was obtained for different artificial skin samples: Lorica, Silicone L7350, pure PDMS, Cutinova and ESE (an epidermal skin equivalent developed by us), and these results were compared to those obtained from excised human skin samples obtained from healthy people after a surgery carried out at the Radboud Hospital of Nijmegen. Later on the human skin samples were analyzed with confocal microscopy and histological images to study the case of the surface properties of skin and determine any possible damage on the Stratum Corneum related to the tribological tests.

KEY WORDS: friction, skin, sliding, artificial turf, abrasion

INTRODUCTION

Despite of the improvements of the last designs of artificial turfs, there are still many issues in achieving a good agreement between the properties of natural grass and artificial turf. Among the tests to perform during the testing phase of a new synthetic turf, skin abrasion is a required parameter to diminish the risks of skin injury of players [1- 3]. To avoid ethical and pragmatic issues when studying the abrasion mechanism on real skin during sliding contact, a new artificial skin equivalent is needed. In previous work, a new Epidermal Skin Equivalent (ESE) with water absorbent capabilities and similar mechanical and surface properties as human skin was developed [4]. The current work focusses on its tribological properties in comparison to ex-vivo human skin, specifically in sliding contact with artificial turf. Hence, NBR, the main constituent of the infill crumb of artificial turf fields, and PE and Nylon 6.6, as main component of the fibers of the artificial grass, were used as a counter material to measure the tribological performance of these systems. Besides, the tests were also conducted on human skin samples to establish a possible association between the abrasion of skin and the selected artificial turf components. To achieve the latter, the surface of the ex-vivo human skin samples were examined via histological images and confocal microscope analysis to determine any possible damage on the Stratum Corneum due to scratching.

MATERIALS AND METHODS

The frictional response of 5 different skin equivalents and ex-vivo human skin samples were studied under normal and high temperature and humidity conditions. The name and properties of the tested materials were: **Lorica**® applied in the development of textiles(Italy); **Cutinova Hydro** used for wound dressing applications from Smith & Nephew plc (UK); **Silicone Skin L7350** supplied by Maag Technic AG, (Switzerland) applied for FIFA test and **pure PDMS** cross-linked in a ratio 20:1, base to curing agent from Dow Corning (Sylgard 184 kit with catalyst). In addition, a new Epidermal Skin Equivalent (**ESE**) based on a mixture of hydrophobic PMDS and PVA hydrogel (as indicated in our previous work [3]) was used. Excised human skin samples, belonging to the stomach reduction of a healthy patience from Radboud Medical Center of Nijmegen, were also measured at the same conditions. Table 1 contains visual information about the samples, their Effective elastic modulus (E_{ff}) center line average roughness (R_a) and the contact angle (CA) of the materials in contact to water drops.

Table 1. Images of the tested samples and selected surface properties: average roughness "R_a", contact angle "CA" and effective elastic modulus "E_{ff}".

	LORICA	SILICONE	CUTINOVA	PDMS	ESE	HUMAN SKIN
Ra (µm)	18.2 ± 5	1.8 ± 0.15	5.5 ± 0.15	14.2 ± 0.6	12.9 ± 3	13 ± 2
CA (˚)	109 ± 6	117.7 ± 5	15.8 ± 5	90.5 ± 5	53.1 ± 6	50 - 60
E (MPa)	7.6 ± 2	6 ± 1	0.2 ± 0.1	1.5 ± 1	0.7 ± 0.1	0.5 – 1

Figure 1a) shows a scheme of the tribo system of artificial – ex-vivo skin samples against counter surfaces selected from the main material components of artificial turf as indicates at Fig. 1 b). The materials used as a pin for the friction tests were selected by considering the composition of an artificial football turf from the third generation. This generation of artificial turfs are composed of a mixture of granulated rubber crumb and sand at the bottom layer with a top layer of pure rubber infill and fibers made of PE or Nylon 6.6 as indicated at Fig.1b). Thus, in this work NBR, PE

and Nylon balls of 30 mm diameter were used as a pin during the tribological measurements to determine the friction of skin in contact to those materials.
Concerning to the operational conditions, forces of 2 and 4 N were applied during the friction tests under normal and high temperature and humidity conditions. The mechanical properties of the pin samples and the operational conditions applied during the friction test are shown in Table 2.

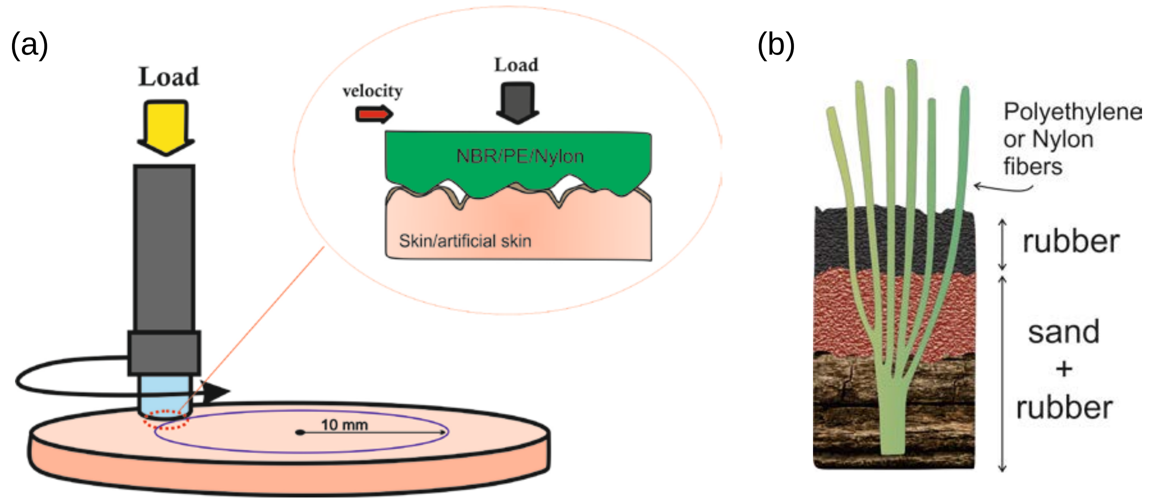


Figure 1. Scheme of the tribo - system a); Layered composition of a third generation of artificial turf, b).

Table 2. Operational conditions of the tribo measurements and properties of the contacting materials.

Force	2 and 4 N		
Velocity	50 mm/s		
Environmental conditions	25 ˚C – 50% RH		37 ˚C – 80% RH
Elastic mod. Pin	**NBR**	**PE**	**NYLON**
	4 MPa	2 GPa	2 GPa
Poisson ration of the pins	**NBR**	**PE**	**NYLON**
	0.49	0.4	0.36
Ø pin	30 mm		

Friction tests

The tribological performance of the samples was studied by using a pin on disk from CSM placed into a climate chamber with temperature and humidity control. Thus, the friction coefficient of the samples was obtained at forces of 2 and 4 Newton at a sliding velocity of 50 mm/s. Normal conditions of 25˚C and 50% relative humidity and high humidity conditions of 37 ˚C and 80% of relative humidity were applied to evaluate the influence of the environment. The tested samples were placed on a metallic-rotary holder by fixing with double-side tape whereas the human skin samples were fixed with stick pins to a piece of cork placed on an special stainless steel holder. To determine the maximum pressures at the contact and the indentation depths, the Hertzian contact model was applied to each tribological system. Thus, considering the mechanical properties of the contacting materials and the operational conditions of the measurements, the maximum pressures at the contact were ranging from 120 - 139 kPa to 152 - 175 kPa for the applied forces of 2 and 4 N, respectively. The contact radii was found between 2.6 - 2.8 mm for 2 N force and 3.30 - 3.5 mm for an applied force of 4 N.

Confocal microscope

The surface roughness of the samples was analysed with a a laser confocal microscope VK 9700 from Keyence at a magnification of 10x and z-axis resolution of 1 nm. Although other the roughness parameters were also obtained, only the arithmetic mean (R_a) of the roughness distribution is used to compare the human surface roughness of the human skin samples before and after the tribological measurements. Immediately after the friction tests the samples were taken to the confocal microscopy to determine possible changes on the roughness at the track. Subsequently, the tested samples were chemically treated to perform the histology of their cross section and determine possible damage on the Stratum Corneum.

Histological procedure

Human skin samples were donated by the Radboud Hospital of Nijmegen with the consent of the patients, the agreements of the Ethical Committee of the Hospital and the approval of the University of Twente. 10 Human skin samples of 30 mm diameter excised from surgical proceedings were mounted on a special stainless steel holder and fixed with pins in a piece of cork. The samples belonged to the abdomen of an unknown person, previously informed about the measurements and who informed consent.

After measuring the roughness of the skin-tested samples, small pieces of skin belonging to the track where the friction was measured were taken for histological analysis. The samples were cut with a biopsy punch of 8 mm diameter and, immediately after, they treated with 10 % formalin for 4 hours and ethanol 70% afterwards. Later, they were brought into the machine which embedded them in paraffin after 8 hours and paraffin blocks were obtained by mounting the samples in specific holders. Paraffin sections of 6 μm were achieved, dewaxed with histosafe (Adams) and subsequently, rehydrated in decreasing concentrations of alcohol (100 – 50%) and, finally, demineralized water. Eventually, the sections were coloured with Hematoxylin-Eosin (HE) stain and mounted in a glass slide to check the histopathological features with a microscope Axioskop2 MOT (Zeiss) at a magnification of 20x.

3.- RESULTS & DISCUSSION

Friction tests

Frictional tests on 5 different artificial skin equivalents and ex-vivo human skin samples against NBR, PE and NYLON were performed. The results, which were performed 6 times for each material, are summarized by Fig. 2. The presented graphs represent the average and the standard deviation of batches of 6 trials for each case. The friction values were dependent on the applied force as shown in Fig. 2 a) and c) pointing the relevance of the real area of contact in the friction value of soft materials.

Regarding to the influence of the environmental conditions, the results suggest minor influence of the humidity or the temperature on the tribological performance of the samples as showed Fig.1 a) – c) and b) – d).

Normal vs high humidity-temperature conditions

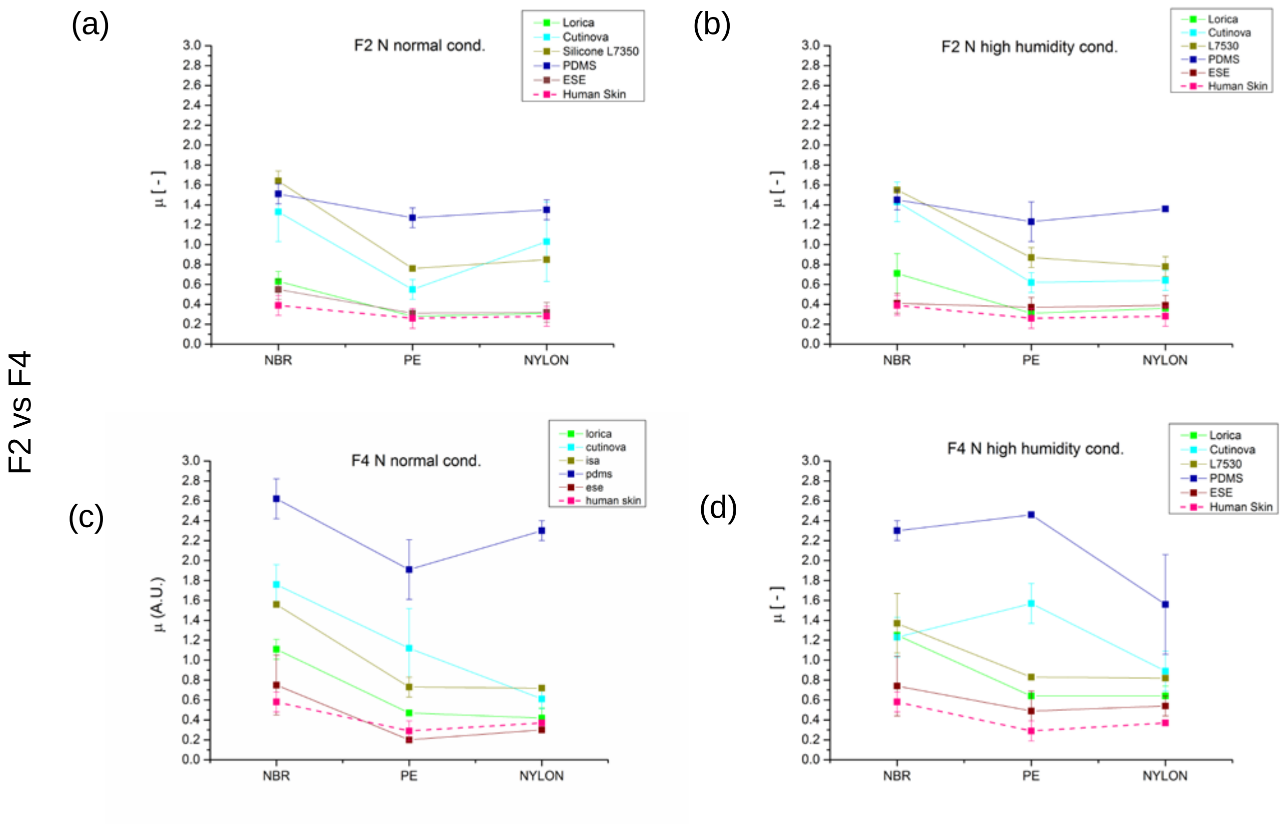


Figure 2. Graphs of the frictional behaviour of the tested samples against NBR, PE and Nylon pins at forces of 2 and 4 Newton (up and down, respectively) and at normal and high humidity environmental conditions (left and right, respectively).

According to the results showed at Fig. 3, higher friction values were obtained when performing the measurements with an NBR pin while, PE or NYLON pins addressed to lower friction values, suggesting the possible use of these materials either as coating or main material as infill materials for new turf designs.

Moreover, the test also confirmed the good agreement between Lorica samples, in concordance with those obtained by Derner et al. [6] in previous work, and the newly developed ESE with the human skin results.

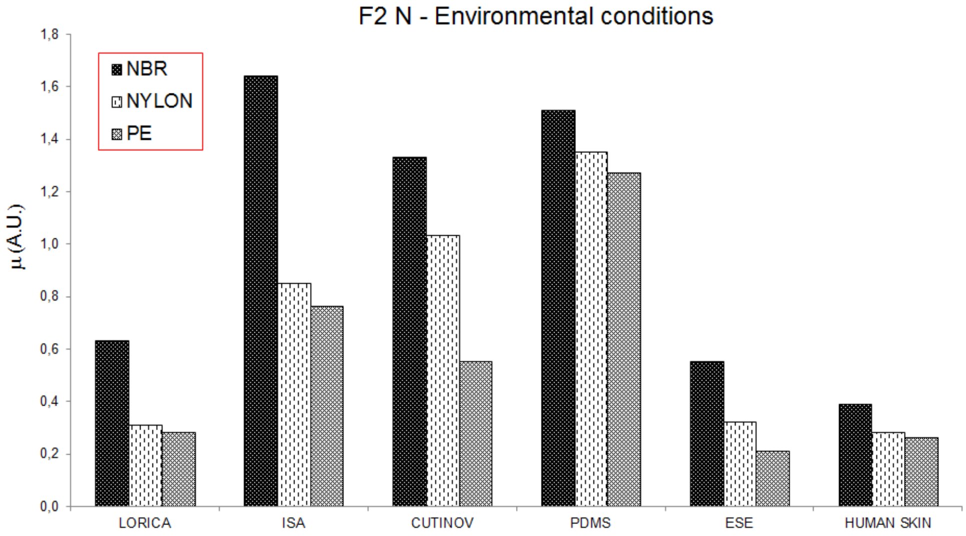


Figure 3. Comparison of the friction values for the artificial skin equivalents and the human skin samples as a function of the used pins: NBR, PE and Nylon.

Confocal Microscope and histology

Confocal measurements showed differences in the roughness of the skin samples tested against NBR and the surface of those tested with PE and NYLON as indicated Fig.4. Higher roughness suggest a higher deformation of the skin samples tested against NBR samples which is in agreement with the histological cross sections. However, based on these results it is not possible to conclude that NBR can trigger skin damage, since the histological images do not show surface damage when comparing with non-tested human skin samples as indicated at Fig.5. Moreover, these experiments were performed at low contact pressures compare to those which appear at the contact location where an impact occurs.

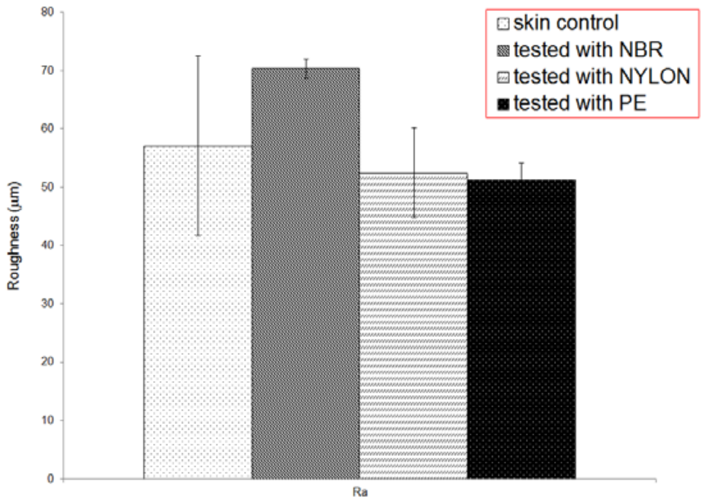
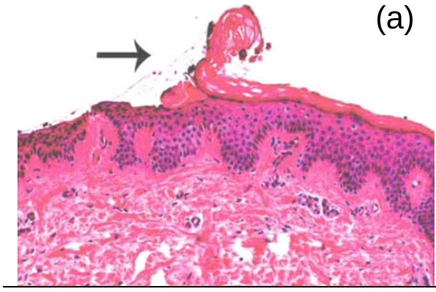
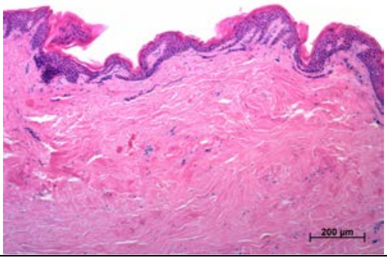
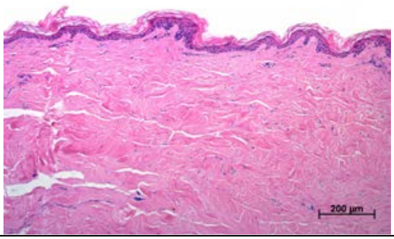


Figure 4. Roughness of the human skin samples after the tests performed against NBR, PE and Nylon and comparison to a non-tested human skin piece (skin control).

Table 3. Histological images of human skin samples after artificial turf testing (a), tribological test against NBR ball (b) and non-tested samples for comparison (c).

(a)	(b)	(c)
		
Human skin against artificial turf, illustrating removal of SC (with permission from ref. [7]).	Human skin against NBR	Human skin control

CONCLUSIONS

Tribological tests were performed on different artificial skin equivalents and human skin samples against the main components of artificial turfs, NBR, PE and Nylon. The results confirmed the good agreement of the human skin friction values and those obtained for the artificial samples ESE and Lorica. Besides, the friction values obtained for human skin samples in contact to NBR, PE and Nylon showed higher values for the infill turf when compared to the fibbers which suggests a greater role of NBR in the possible abrasion of skin during sliding contact. The results were also obtained either for the artificial skin equivalents in contact with NBR rubber, even at low loads.

Despite of the high friction values during the test with NBR, the histological sections did not show any damage of the Stratum Corneum.

Regarding to the environmental conditions, the results do not indicate variability when increasing temperature and/or humidity. However, further research needs to be conducted to evaluate the effect of the hydration in the tribomechanical performance of these samples and fully simulate their agreement with the friction performance of human skin at different hydration degrees. Besides, deeper investigation on the contact NBR – human skin has to be address at higher pressures to simulate the operational conditions during the sliding contact of a football player on artificial grass.

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