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Tribological behaviour of skin equivalents and ex-vivo human skin against the material components of artificial turf in sliding contact

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ABSTRACT

This research aims to analyse the interaction of three artificial skin equivalents and human skin against the main material components of artificial turf. The tribological performance of Lorica, Silicone Skin L7350 and a recently developed Epidermal Skin Equivalent (ESE) were studied and compared to ex-vivo human skin samples. The surface of the ex-vivo skin was analysed via confocal microscopy and histology. The results indicated a similar performance of the Lorica and ESE samples when compared to the ex-vivo skin whereas the Silicone Skin L7350 showed significant differences. The results suggested also a key role of the intrinsic properties of the NBR material to the friction against human skin, compared to PA 6.6 or PE surfaces in a similar sliding contact.

1. Introduction

The use of artificial grass for sports pitches has clear ecological and economic benefits [1–3] over the use of natural grass, in countries with an extreme hot or cold climate, or for places with limited rainfall. Moreover, it can be used intensively for almost 24 h a day and seven days per week [4]. The quality of the turf and the comfort during the game, essential aspects from the users point of view, are currently secured by the FIFA® Quality Concept for Football Turf [4] requirements, which are based on a series of laboratory tests that the manufacturers of artificial grass must perform before the turf can be applied to football pitches. The tests are among other aspects developed to standardise the quality of the turf and guarantee the safety of football players during the interaction with the grass. The turf is tested in terms of durability, climatic resistance and player-to-surface interaction [1,3,4]. The latter evaluation involves the assessment of the tribological behaviour of a skin equivalent material in contact with artificial turf, with the aim to examine the risk of skin abrasion and high skin friction e.g. for a sliding tackle. The need to assess this behaviour is clear from the documented incidences of skin injuries and player's discomfort in relation to player's interaction with artificial turf [5–12]. Silicone Skin L7350 is currently used as artificial skin equivalent in the FIFA test [4], most likely based on the overall mechanical properties and availability of the silicone rubber material. It is, however, highly questionable whether or not sliding safety and further optimisation of comfort during sliding tackles on artificial grass can be achieved with similar mechanical properties only. As such, new artificial skin equivalents have been developed and used in explorative tribological studies, focussed on simulating the proper frictional performance depending on parameters including age, anatomical region or hydration of the skin [13]. Limitations exists in simulating the tribo-mechanical performance of skin properly over the full range of conditions [13–16]. The recently developed skin equivalent by Nachmann and Franklin [17] shows a good agreement in dry and moist conditions to human skin, but the model needs to be analysed in a broader range of conditions. Currently, commercial available samples are used as skin equivalent for different applications, including soft biocompatible materials [18–20]. Stiffer samples such as Lorica have been used as a skin equivalent to study the interaction against textiles and non-woven fabrics [21–24]. The counter surface, artificial turf, is typically composed of a layer of sand infill to ensure the fibres stand vertical with a top surface of granulated Acrylonitrile-Butadiene rubber (NBR) and Styrene-Butadiene rubber (SBR) to enhance the impact absorbency of the turf. This turf has also longer fibres compared to the previous generations (>55 mm) and they are usually made of Polyethylene (PE) instead of Polyamide 6.6 (PA 6.6). From this it is clear that there is not just a single artificial turf surface which can be used for pin-on-disk

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tests for example, but a series of possible surfaces as a function of time and operational conditions. Yet, in all cases there will be an interaction of the skin with fibres and with the infill.

The aim of this work is limited to measuring and understanding the relative contributions to sliding friction of the infill material and of the fibre material separately, with respect to the currently used skin equivalents, a newly developed skin equivalent material and in comparison with ex-vivo skin. As such, the interactions of three mechanical skin equivalents and excised human skin in contact with the material components of the artificial turf was investigated by pin-on-disk experiments. The specific role of each turf component during the sliding contact was evaluated in terms of the adhesive and the elastic properties of the involved materials. NBR as the main constituent of the infill crumb of artificial turf fields, and PE and PA 6.6, as main component of the fibres of the artificial grass, were used as counter materials. Such a comparison has not been made before and the results could contribute to enhanced turf design [21,22,25–28], as data from this work can serve as friction data for a Finite Element based analysis of player – turf interactions during sliding tackles. Surface changes of the ex-vivo skin samples were analysed by histology and confocal microscope measurements. Additionally, an analysis of the elasticity and the frictional performance of the skin was made based on the two-term friction model and based on the evolution of the elastic modulus with the length scale [29,30].

2. Materials and methods

Three skin equivalents and ex-vivo human skin samples were studied. The synthetic materials were cut in circular pieces with a diameter of 30 mm and a thickness of 2 mm. Two were commercially available, i.e. Lorica®, a synthetic leather made of polyamide fleeces and polyurethane applied in the development of textiles (Italy); and Silicone Skin L7350 a silicon-based organic polymer patented by Maag Technic AG, (Switzerland) and utilised for the FIFA test. In addition, a recently developed skin equivalent [19] composed of a mixture of PDMS and PVA hydrogel crosslinked with glutaraldehyde and referred to as Epidermal Skin Equivalent (ESE), was used. Fig. 1 shows the artificial skin materials together with their elastic moduli [19]. Temperature and humidity considerably affect the tribo-mechanical performance of the skin, especially its elastic modulus and adhesive properties of the system and, subsequently, the friction coefficient [33]. Hence, the friction behaviour of the synthetic materials was investigated at both standard (25 °C and 50% relative humidity) and extreme (37 °C and 80% relative humidity) climate conditions. Furthermore, ten ex-vivo human skin samples from surgical proceedings belonging to the abdomen of one overweight anonymous person were evaluated at standard conditions. No measurements were performed at extreme conditions with the skin samples because once excised from the body they do not react to humidity or temperature changes in the same way as human skin does. The excised samples were donated by the Radboud Hospital of Nijmegen with the consent of the patient, the agreements of the Ethical Committee of the Hospital and the approval of the University of Twente. The use of abdomen skin introduces a simplification as it differs partially from the skin of the leg due to roughness differences and the presence of hair in the latter case. In this case, differences due to the roughness between the skin of the leg and the abdomen are not expected due to the high normal forces applied. It might be that the presence of hair lowers the coefficient of friction however, this is still unclear and the possible differences fall within the likely scatter in performance that exists intra and inter-individual [13,34].

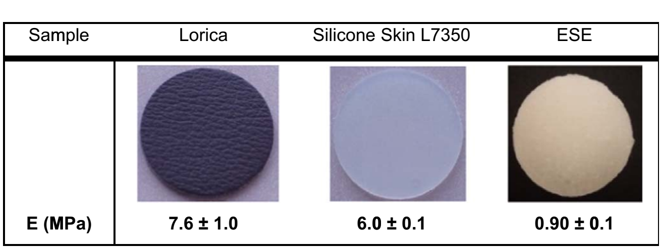

Fig. 1. Images of the samples and their elastic modulus obtained from indentation tests [from Ref. [19]].

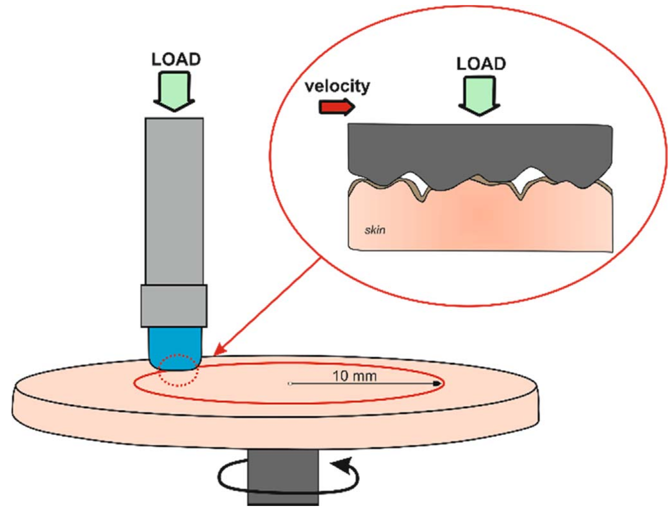

Fig. 2. Schematic illustration of the tribological system.

2.1. Tribological measurements

The tribological measurements were performed on a HC 4057 pin-on-disk machine (CSM, Switzerland) placed into a climate chamber with temperature and humidity control. Ex-vivo skin and artificial skin equivalent samples of 30 mm diameter and 2 mm thickness were prepared and evaluated. The friction measurements were conducted at a distance of 10 mm from the centre of the disk samples, see Fig. 2, at standard and extreme climate conditions. Cylindrical pins of 10 mm, made of NBR, PE, PA 6.6 with a spherical tip of 15 mm radius were used as a counter surface. Fig. 3 shows a 3D image of one of the pins, which were all machined in the same way, and the specifications of the surface roughness, similar for each pin and defined by R_a, R_q, R_{pv} and R_{sk}. Normal loads of 2 N and 4 N were applied during the friction tests to ensure similar pressures at the contact to those originated at the FIFA test friction method [4], assuming Hertzian contact conditions. The tests were performed at a velocity of 50 mm/s to avoid the influence of heating.

The skin equivalent samples were placed on a rotary holder and fixated with double-sided tape whereas the human skin samples were mounted on special stainless steel holders (AISI 316) and clamped at cork pieces with pin sticks as shown in Fig. 4(a). Fig. 4 (b) shows the pin-on-disk tester with human skin sample on the holder during one for the measurements.

After the tribological measurements, the skin samples were taken to the Dermatology Department of Radboud University Medical Centre Nijmegen, where the histological procedures were performed.