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# Skin injury due to artificial turf

The skin as a readout system

Wilbert van den Eijnde

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### **Skin injury due to artificial turf: The skin as a readout system**

Thesis Radboud university medical center, Nijmegen, the Netherlands,  
with summary in Dutch.

The research presented in this thesis was performed at the Department of Dermatology  
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# Skin injury due to artificial turf

The skin as a readout system

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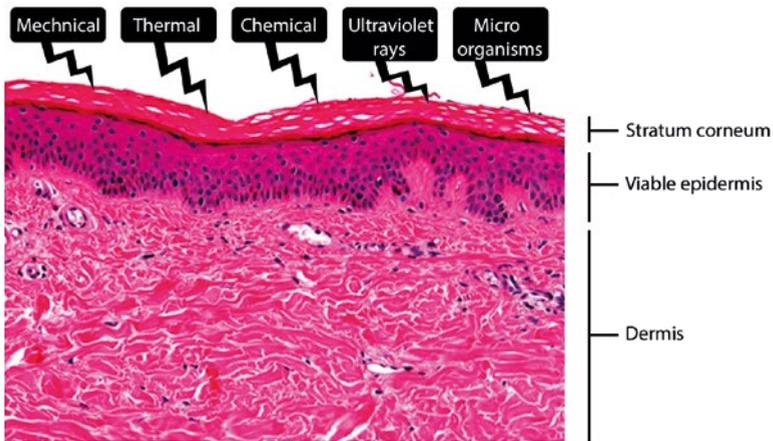
# 1

## General introduction and outline of the thesis



## Skin and its barrier function

The skin has an average surface area of 1.8 m<sup>2</sup> and an average thickness of 1.2 mm.<sup>1</sup> The main function is to protect the internal tissue from different kind of external risks. With its ingenious multi-layered composition, it provides specific protective functions to mechanical and thermal load, chemical permeation, ultraviolet rays and micro-organisms (Figure 1). The skin is able to respond and capable to self-repair.



**Figure 1** The skin and the barrier function to external risks. Normal skin histology (200x magnification) of HE stained skin showing from top to bottom, the stratum corneum, the viable epidermis and the dermis.

The upper layer, the stratum corneum (SC), is formed by tightly packed flattened anucleated cells, called *corneocytes* which are embedded in an intercellular lipid matrix. This structure is often mechanically described as a *brick-and-mortar* model.<sup>2,3</sup> Delamination studies of the SC revealed an intercellular failure path rather than a fracture of the corneocytes. It is assumed that this is why environmental influences, as e.g. higher room temperatures and humidity, decreases the bond strength significantly.<sup>4</sup> This thin (8 to 20  $\mu\text{m}$ ) rigid superficial layer plays an important role in the barrier function of the skin to physical risks.<sup>1</sup>

The SC is the end stadium of the proliferation and differentiation process which starts at the basal layer of the epidermis (30 to 100  $\mu\text{m}$ ) where nucleated keratinocytes divide and subsequently differentiate. The typical time period of this turnover process is two to three weeks.

The dermis is much thicker (0.8 to 1.2 mm) and contains collagen, elastin, capillaries, nerves, sweat glands and hair follicles. The dermis plays an important role in the thermo-regulation and shock absorption.

## The skin as a sensory system

The skin also serves an important role in the sensory pathway via its nervous system. Specialized peripheral sensory neurons known as *nociceptors* in the dermis alert us to potentially damaging stimuli, and transducing these stimuli into long-ranging electrical signals that are relayed to higher brain centres.<sup>5</sup>

Nociceptive fibres are classified on the basis of their conduction velocity, sensitivity and threshold to mechanical, thermal and/or chemical stimuli. C-nociceptors are the smallest in diameter (<2 µm) and demonstrate the slowest conduction (0.4-1.4 ms<sup>-1</sup>). A-nociceptors are bigger (2-5 µm) and support conduction velocities of approximately 5-30 ms<sup>-1</sup>. Generally, A-nociceptors elicit rapid, first phase of pain, which is 'sharp' in nature, whereas C-nociceptors evoke a second wave of 'dull' pain.<sup>6</sup> The cutaneous nociceptors responding to thermal stimulations are largely polymodal, as they can be activated by thermal, mechanical and/or chemical stimuli. The threshold to thermal heat varies between 39 °C and 51 °C.<sup>5</sup> More specific, the thermal pain threshold is assumed to be 43 °C.<sup>7</sup> The mechanical pain threshold to pressure is assumed to be 0.2 MPa (20 Ncm<sup>-2</sup>).<sup>7</sup>

From pain studies is known that pain perception due to a stimulus is depending on various psychophysiological factors at both sensory, cognitive and affective level (Table 1).<sup>8</sup> The interactions between the different psychophysical factors during the interpretation of a stimulus in the brain can be complex, are subjective and difficult to measure. The outcome however can well be measured. The most common way in psychophysical research, the scientific study of the relation between stimulus and sensation, is to ask the subject what he or she experienced and at what intensity.<sup>9</sup> A well accepted method to rate experienced pain or discomfort for example is based on a questionnaire where subjects have to mark their experienced pain on a visual analogue scale running from 0=no pain to 10=worst pain imaginable.<sup>10</sup>

As pain, comfort is a complex concept, consisting of a mix of feelings, perception, mood and situation (Table 1).<sup>14</sup> In human-product interaction, (dis)comfort is a popular research topic with application in areas such as sitting, hand tools and running footwear.<sup>15,16,17</sup>

Fleming et al. specifically studied the players' perceptions of artificial sports surfaces for field hockey, since the player should be comfortable and confident with the surface.<sup>18</sup> After analysis, five important dimensions were derived, which determine the assessment of sports surfaces for field hockey by players. Player-surface interaction appeared to be one important dimension which contains three constructs: abrasiveness, hardness

**Table 1** Overview of definitions of relevant psychophysical sensations.

Sensation	Reference	Definition
Pain	Loeser et al. <sup>11</sup>	An unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of such damage.
Comfort	Kölsch et al. <sup>12</sup>	1. Absence of discomfort.
	Slater <sup>13</sup>	2. Pleasant state of physiological, psychological and physical harmony between a human being and its environment.
	Vink et al. <sup>14</sup>	3. Convenience experienced by the end-user during or just after working or using the product.
Discomfort	Kölsch et al. <sup>12</sup>	Perceived feeling of uncomfortable body parts.

and grip. It is likely that these constructs are also applicable for artificial soccer turf. The question is whether these constructs are predictors for perceived sliding (dis)comfort in particular on artificial turf.

## Acute skin injuries, mechanical load and healing process

Although the human skin is flexible and has a huge capability to absorb mechanical load, like any other material, it has its limitations resulting in failure or breakdown. Skin failure or wound, is defined as a disruption of the normal anatomic structure and function of the skin.<sup>19</sup>

From a biomechanical perspective, an injury is “equivalent to the failure of a machine or structure” and results from an energy transfer to the tissue.<sup>20</sup> The mechanical properties of the skin such as stiffness, ultimate strength, and critical stress, govern how the skin responds to mechanical loads.<sup>21</sup>

Due to different load mechanisms, characteristic skin failure occurs which lead to different types of acute cutaneous wounds (Figure 2).<sup>22,23,24,25,26</sup>

How failure occurs depends on: the nature of the load and its velocity; the magnitude of energy transfer; and other intrinsic factors such as age and body location. In addition, extrinsic factors such as temperature, humidity or counter material can also influence the failure of the skin.

In general, acute and chronic wounds can be distinguished depending on how the repair process proceeds. Acute wounds, in comparison to chronic wounds are able to successfully repair themselves in an orderly and timely process. Although relevant, chronic wounds fall beyond the scope of this research.

Load	Orientation	Wound	Depth	Repair time [weeks]	Clinical appearance
Shear	In-plane	Abrasion	Epidermal	1-3	
Shear	In-plane	Blister	Dermal-epidermal	1-2	
Shear	Out-of-plane	Puncture	Hypodermal	2-3	
Shear	Out-of-plane	Laceration/cut	Hypodermal	2-3	
Tension	In-plane	Tear	Hypodermal	3-4	
Compression	Out-of-plane	Contusion	Hypodermal	2-3	

**Figure 2** Overview showing the relation between mechanical load, type of wound, depth, repair time and corresponding typical clinical appearance.

The normal recovery time of acute wounds depends on the depth and involved area and can take up to three weeks. During this period, a complex orchestrated dynamic process involving inflammation, proliferation and remodeling takes place.<sup>26</sup>

Tissue injury is characterized by microvascular injury and therefore extravasation of blood into the wound followed by rapid constriction of the injured blood vessels.<sup>23</sup> The blood-filled wound is first closed by a *fibrin coagulum* or blood clot. If the surface dries out a stiff scab is formed that protects the wound.<sup>10</sup> This triggers the first phase of wound healing: the inflammatory process. First *granulocytes* (24 to 48 h) and thereafter *macrophages* (48 to 72 h) are infiltrating into the wound. Macrophages appear to act as the key regulatory cells for repair. They release *cytokines* and growth factors, recruiting and activating *fibroblasts*, *keratinocytes* and *endothelial cells* to repair the damaged blood vessels.<sup>23</sup> The proliferative phase starts at about 72 hours and lasts for two weeks. It is characterized by skin resurfacing and dermal restoration in which the earlier provisional

matrix is replaced with newly formed granulation tissue.<sup>27</sup> As soon as the new tissue is formed, the remodeling phase of wound healing starts to reorganize structural integrity and functional competence.<sup>26</sup>

Although the effects of acute skin trauma such as cuts, abrasion and lacerations are usually not presented at emergency rooms they need proper treatment to prevent complications, in particular infections.<sup>28,29,25</sup> Infections can be caused by fungi, viruses, and bacteria like Methicillin-Resistant Staphylococcus Aureus (MRSA).<sup>19,30,31</sup> Complications associated with infections are: tissue damage, foreign body contamination, and bacterial inoculation.<sup>25</sup>

The skin is well capable to repair the wound itself, however wound management can help to prevent further bacterial inoculation and clean the wound of foreign bodies which has a positive effect on the rate and/or effectiveness of the healing process.<sup>32</sup>

## Artificial turf systems for soccer

As the soccer's global popularity increases, the climate plays a greater part in limiting the further development. In unfavourable weather conditions, the use of natural grass fields is limited, and athletic performance suffers.

The development of alternative artificial sport surfaces started in the 60's (Figure 3). For baseball, in 1966 the first synthetic grass carpet, made of nylon (PA) fibres, was installed in the Houston Astrodome by Monsanto (United States of America). Soon, nylon was replaced by polypropylene (PP) which is softer. This design is referred to as the *first-generation* artificial turf systems. The *second-generation* fields were introduced in the late 1970's. These pitches had longer tufts, spaced more widely apart and a sand infill which provided more stability.<sup>33,34</sup> These advantages resulted in rapid acceptance of second-generation artificial turf pitches in hockey.<sup>18</sup> For soccer on the other hand, second-generation artificial turf pitches were not suitable due to different ball characteristics and painful skin injuries caused by the abrasiveness of sand infill. Although introduced in soccer, these type of pitches were for this reason banned in the United Kingdom in 1988.

The introduction of synthetic infill systems also known as *third-generation* artificial turf contributed to the acceptance of artificial turf pitches in soccer over the last two decades. This new generation system had longer fibres, which were even more spaced further apart compared to previous generation artificial turf systems. Instead of polypropylene (PP), the fibres were made of polyethylene (PE) and a rubber infill was added to the sand. These changes mimic the natural grass characteristics more.<sup>33</sup> The benefits over natural grass, as low maintenance costs, high playing intensity and consistency are generally recognized. The popularity of third-generation turf pitches was boosted after the acceptance into the laws of the game since July 2004.<sup>35</sup> Currently, in the Netherlands alone, more than 1500 third-generation soccer turf systems are installed and in use.

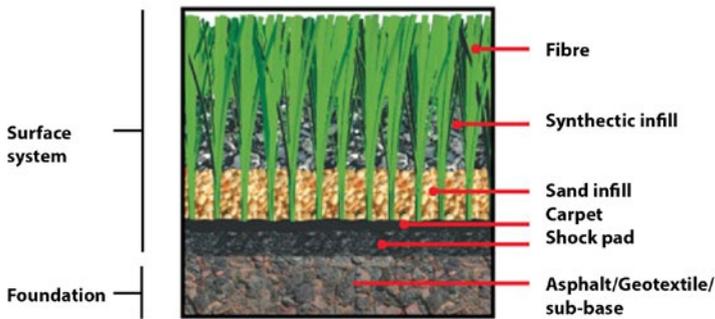


**Figure 3** Summary of the history of artificial turf in soccer.

### Third-generation artificial turf system

Although a large variety of artificial turf configuration exists, it always consists of a surface system (infill, carpet, shock pad) and a foundation (asphalt, geotextile and sub-base) (Figure 4).<sup>36</sup>

The foundation provides stability and is important for the water drainage. The surface system is mainly considered to directly influence the game performance. A wide variety of materials are used for the carpet, infill and shock pad. The tufted carpet can have a pile height up to 65 mm. The fibres can either consist of one piece (monofilament) or multiple pieces (fibrillated). They can differ in shape, length and material. Polypropylene (PE) and polyethylene (PP) are most often used.



**Figure 4** Schematic configuration of a third-generation artificial turf pitch.<sup>36</sup>

The synthetic infill material, which is important for both the traction and shock absorption characteristics can either be made from recycled tires (Styrene-Butadiene-Rubber (SBR)) or can be specially made of e.g. thermoplastic elastomers (TPE) or Ethylene Propylene Diene Monomer (EPDM).<sup>24</sup>

Finally, a shock pad is installed mainly to modify the shock absorption properties. Generally, rubber or cell-foams with a thickness, varying from 8 to 35 mm are used.

## Artificial turf and skin injuries

The introduction of artificial turf in soccer, is strongly associated with abrasion type of skin injuries (Figure 5). Depending on the injury mechanism, skin-surface contact can lead to abrasion, laceration or contusion injuries. Regarding sliding induced skin trauma, it is assumed that friction is causing abrasion wounds.

Abrasion injuries can be defined as superficial removal of differentiated keratinocytes and keratinized cells from the underlying dermis.<sup>29</sup> The clinical appearance of an abrasion can be characterized by an irregularly denuded epidermis and an exposed upper dermis. Deep, dermal-epidermal abrasions wounds also show punctate bleeding and tissue exudation. In some literature, this type of wound due to artificial turf contact is referred to as "turf burn". This suggests that the injury is caused part by abrasion and part by burn due to frictional heat.<sup>22</sup>



**Figure 5** Typically abrasion type of injury on the thigh caused by a sliding movement on a third-generation artificial turf configuration.

A well accepted method used in studying product-skin contact in tribology, the science of interacting surfaces in relative motion, is the so-called system approach. A system is seen as a set of elements interconnected by structure and function. In the case of skin tribology, a system consists of an interaction between skin and product surface within a specific environment possibly in the presence of a lubricant.<sup>37</sup> Operation variables such as pressure or velocity are typically regarded as input conditions of such a *tribo-system*. Friction and wear are the output or result of the system. Tribologists, therefore consider an abrasion injury as a wear characteristic which can be used to classify the intensity of the contact.

### Surface standards for skin abrasion

Looking at the players' perspective, the ultimate aim for any playing surface is to maximize performance and comfort and to minimize injury and the risk of injury.<sup>38</sup> In order to meet these requirements and to gain knowledge on the user safety of artificial turf, many studies have been performed mainly focusing on the comparison with natural grass. The outcomes have led to different standards set by the sports governing bodies around the globe.<sup>35</sup>

Regarding the assessment of the abrasiveness of artificial turf, two instrumental test methods are generally accepted: FIFA test method 08 "Determination of Skin/Surface Friction" and ASTM F1015 "Relative Abrasiveness of Synthetic Turf Playing Surfaces" (Figure 6).<sup>35,39</sup>



**Figure 6** Test foot and apparatus according to the FIFA method 8 (above) and foam block configuration and experimental setup of the ASTM F1015 method (under).<sup>35,39</sup>

Both methods use skin replacers, silicon and foam blocks, respectively. The FIFA test method 08 uses the difference in pull force of a new and abraded silicon skin over a metal plate as a read-out. Where the ASTM method, uses the weight loss of the foam to determine the abrasiveness of artificial turf. When applying the ASTM method, McNitt et al. reported that third-generation artificial turf systems on average have an abrasiveness index of about half that of traditional second-generation artificial turf.<sup>40</sup>

A limitation of both methods is that they do not simulate realistic vertical forces and velocity of a sliding. Sanchis et al. therefore developed a device to test the friction at realistic sliding conditions. This study showed a good correlation between the increased surface roughness of the tested silicone and players' perception. However, the correlation between the friction coefficient and the abraded silicone was poor.<sup>41</sup> It was suggested that another mechanism of damage could be present.

In general, at the moment, a proper understanding of player-surface interaction and the relation with the surface properties with underlying components (infill, elastic layer, fibres) is lacking. This understanding is necessary to set new standards or to justify existing standards.<sup>24</sup>

## Injury prevention model

Soccer, or football, is the most popular sport practiced worldwide, with 265 million active players, and still expanding.<sup>42</sup> It is played by all ages, male and female. In the season 2013-2014, the Dutch football association, KNVB (Koninklijke Nederlandse Voetbalbond) alone has more than 1.2 million active members.<sup>43</sup>

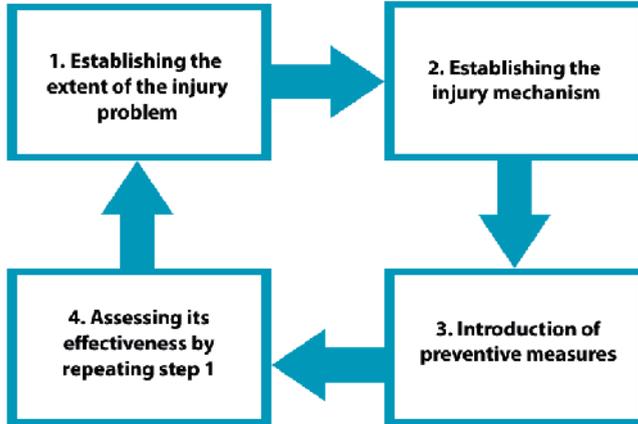
Like any other contact sport, soccer has a relative high risk of injury. Based on well-established epidemiology studies, the incidence of football injuries in adult male players is estimated to be 10 to 35 injuries per 1000 game hours.<sup>44</sup> Assuming, an annual average of 100 hours of football it is estimated that every player will get at least one performance-limiting injury per year. In the Netherlands alone, annually 620 thousand soccer related injuries are registered.<sup>43</sup>

Besides pain and suffering, these injuries result in medical costs and absence at work. Therefore, injury prevention is not only important in sport performance but also has economic and social impact.

The Fédération Internationale de Football (FIFA), as international governing body took her responsibility. In the past decade, the FIFA introduced several initiatives regarding injury prevention e.g. risk management framework, prevention programs like "the 11" and the injury monitoring system during major international tournaments.<sup>45,46,47</sup>

Although various frameworks have been introduced, the proposed prevention model for research studies by Van Mechelen et al. is widely accepted (Figure 7).<sup>48</sup> Ideally, a prevention study follows a four-step method. According to this model, the extent of the injury (step 1)

and injury mechanism (step 2) are the starting points to introduce preventive measures (step 3) and to assess its effectiveness (step 4).



**Figure 7** The four step sequence model for injury prevention research presented by Mechelen et al.<sup>48</sup>

### Step 1: Establishing the extent of the injury problem

From epidemiological injury studies, it can be concluded that the majority of football injuries (41 %-81 %) are caused by physical contact.<sup>49,50,51,52,53,54,55</sup> The physical contact is mainly attributed to player-player contact during tackling actions. Only Fuller et al. separately reported the incidence rate of player-surface contact.<sup>52</sup> Of all reported injuries of male players, 6.6 % (1.67 injuries/1000 player hours) of those on artificial turf are from player-surface contact versus 7.5 % (1.87 injuries/1000 player hours) on natural grass ( $p=0.72$ ).<sup>52</sup> Unfortunately, Fuller et al. did not correlate the type of injury to this player-surface injury mechanism.<sup>52</sup> Until now, there are no published data available on the skin injury incidence rate caused by player-surface contact.

In general, an overview of the incidence and severity of skin related injuries is lacking at the moment. Thereby, conflicting results seem to be reported.<sup>52,56,57</sup>

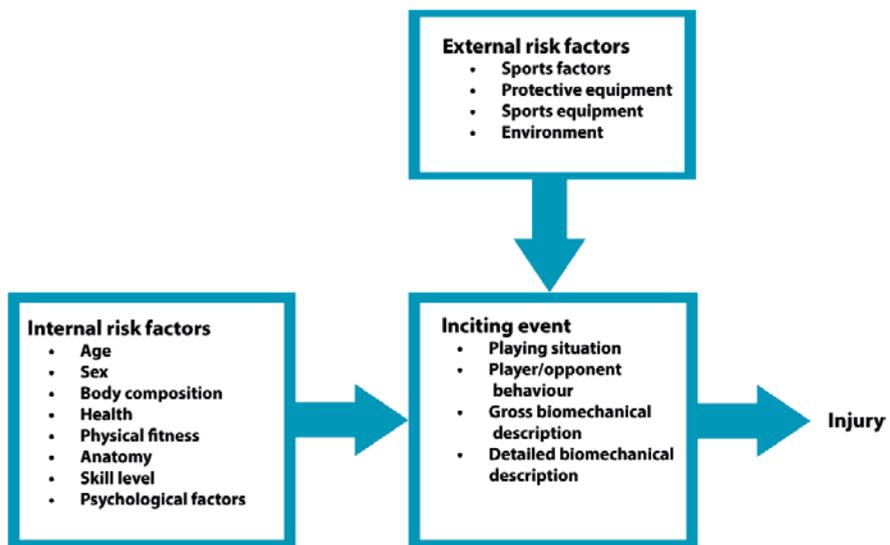
### Step 2: Establishing the skin injury mechanism

The most critical step in the sequence is to establish the cause of an injury.<sup>58</sup> This includes obtaining information and insight in the correlation between risk factors and injury mechanism.

Different multifactorial models have been proposed to study injury causation. In their epidemiological model, Meeuwisse et al. suggested that although an injury may appear to have been caused by a single event, a combination of internal and external risk factors may have made a player more susceptible to injury in a given situation.<sup>59</sup> According to

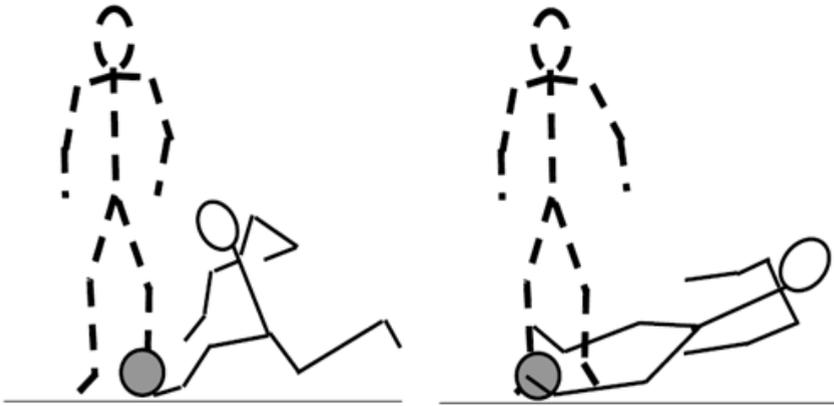
McIntosh's biomechanical causation model, risk factors must explain how the event either resulted in the excess of tolerated load or reduction of tolerance levels.<sup>21</sup>

Bahr et al. combined both models in assuming that load and load tolerances can be influenced by either internal and external risk factors and the event itself (Figure 8).<sup>58</sup> Regarding to the research objective the inciting event of interest is the sliding tackle. In a study by Fuller et al., six different tackle actions were identified.<sup>60</sup> The applied definition of a tackle action is any attempt to dispossess an opponent of the ball. In this thesis, the so-called sliding in one footed tackle and a two footed horizontal jumping tackle, are of interest because these involve skin-surface contact (Figure 9).



**Figure 8** Comprehensive model for injury causation adapted from Bahr et al.<sup>58</sup>

It is documented that of 8572 assessed tackles in 123 matches played during men's 1998 World cup, 1999 under-17 World cup and 2000 Olympics, 2172 (average of 17.7 per match) sliding in tackles and 147 (average of 1.2 per match) horizontal jumping tackles were performed. Although a horizontal jumping tackle is less performed, the risk of injuries is significantly higher (40.8 injuries per 1000 tackles compared to 18.4 injuries per 1000 tackles). Whether the skin injuries are caused by player-player or by player-surface contact cannot be resolved, let alone the effect of the type of surface. More in general, essential biomechanical data of a sliding tackle regarding the kinematics and energy transfer is lacking at the moment. Therefore, this thesis wants to explore the biomechanical load on the skin during a sliding tackle in more detail.



**Figure 9** Two identified tackling actions resulting in skin surface contact. The sliding in – technique [left] and two footed horizontal technique [right].<sup>60</sup>

## Objective and outline of this thesis

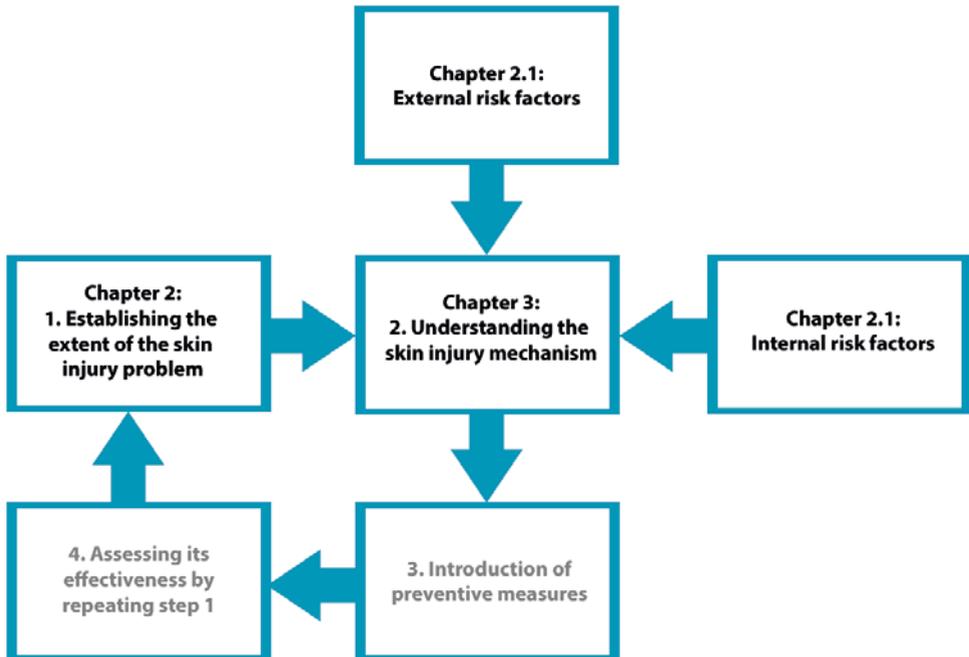
The main objective of this thesis is to acquire knowledge on the assessment of artificial turf for soccer with respect to skin-surface contact during a sliding tackle. This knowledge should contribute to an improvement of artificial turf surfaces with regard to sliding friendliness, which lead to safer and more comfortable artificial sport surfaces in the near future.

To achieve this, the following sub-goals are described:

- Proposing measurement tools to assess the sliding friendliness of artificial turf pitches using the player as a readout system;
- Contribute to the unveiling of the theory of acute skin injury mechanism due to skin-surface contact during a sliding tackle;
- To explore the load tolerance levels of skin during skin-surface contact.

The injury prevention model described by van Mechelen et al. was taken as the framework for this thesis (Figure 10).<sup>48</sup> The focus of the research is on the first two steps of this prevention model. It is the responsibility of manufacturers and sport governing bodies to introduce preventive measures and assess the effectiveness of it.

Until now, the focus of epidemiology studies in soccer are focused on severe type of injuries, which result in one or more days of absence. It is assumed that acute skin injuries are underestimated and occurring more frequently according to players' perspective than any other type of injuries.<sup>61,62,63,64,65</sup> These injuries are of interest because they cause discomfort and may influence the players behaviour, consciously or subconsciously.



**Figure 10** Schematic outline of the thesis in relation to the comprehensive injury causation model according to Bahr et al. integrated in the four step sequence model for injury prevention research according to by Mechelen et al.<sup>48,58</sup>

In **Chapter 2** we aimed to explore the first step of the injury prevention model: the skin injury extent. The survey started with an overview (**Chapter 2.1**) of the current knowledge regarding the skin injury extent and injury mechanism of acute skin injuries in soccer based on a literature research.

Knowledge of the players' perception is an import driver in product development and assessment. At the moment there is no standardised questionnaire available which can be used in user trials. In **Chapter 2.2** we aimed to develop and validate a psychometric instrument which measures the overall performance and sliding friendliness of artificial turf pitches. In order to improve the sliding friendliness it is important to know which parameters are important. Although, some internal and external risk factors are published in literature we aim to identify predictors for sliding friendliness with the aid of the developed questionnaire.

In addition, the question was addressed what the clinical and immunohistological effects of a sliding on artificial turf are (**Chapter 2.3**). Although invasive studies provided

unique valuable insight in the biological response of the skin it cannot be used as a quantitative assessment method. Therefore, we aimed to develop and validate a non-invasive method which uses a sliding induced skin lesion as a readout for sliding friendliness (**Chapter 2.4**). It was hypothesized that the wear characteristic is related to the intensity of the contact and correlates with the experienced discomfort or pain.

In **Chapter 3** the objective was to provide a deeper understanding in to the skin injury mechanism during skin-surface contact. This will contribute to develop new standards and new sliding friendly products. Knowledge in this field is lacking at the moment. More in general, information on skin damage due to skin-material interaction is scarce. Not only the clinical appearance of the injury but also morphologic changes are of interest. For ethical considerations it is not desirable to study the micro-morphology of the skin resulting from skin-material interactions in an invasive way. Therefore, the aim was to develop a non-invasive *in vivo* model using Reflectance confocal microscopy (RCM) to obtain morphological data on skin damage (**Chapter 3.1**).

Currently, there is a shortage of biomechanical data regarding the acute skin injury mechanism that is involved in player-surface contact in soccer on artificial turf. It was hypothesized that peak loads during the landing phase are an important factor in causing an acute skin injury. In an explorative study it was aimed to gather load data and correlate this with observed skin lesions (**Chapter 3.2**).

With the obtained biomechanical load data, a laboratory set-up was built which simulates the load of the impact of a sliding tackle (**Chapter 3.3**). The aim of this laboratory set-up and using *ex-vivo* skin was to explore the load tolerance levels of the skin during the impact on artificial and natural grass. These load tolerance levels are the first step in defining the design space or setting requirements for sliding friendly artificial turf pitches.

In **Chapter 4** the general results obtained in this thesis are discussed in the light of recommendations for further research and implementation of proposed assessment techniques.

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# 2

Establishing the extent  
of the skin injury problem



# 2.1

## Understanding the acute skin injury mechanism caused by player–surface contact during soccer: A survey and systematic review

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## Abstract

**Background:** Superficial skin injuries are considered minor, and their incidence is probably underestimated. Insight into the incidence and mechanism of acute skin injuries can be helpful in developing suitable preventive measures and safer playing surfaces for soccer and other field sports.

**Purpose:** To gain insight into the incidence and severity of skin injuries related to soccer and to describe the skin injury mechanism due to player-surface contact.

**Study Design:** Systematic review.

**Methods:** The prevention model by van Mechelen et al. (1992) combined with the injury causation model of Bahr and Krosshaug (2005) were used as a framework for the survey to describe the skin injury incidence and mechanism caused by player-surface contact.

**Results:** The reviewed literature showed that common injury reporting methods are mainly based on time lost from participation or the need for medical attention. Because skin abrasions seldom lead to absence or medical attention, they are often not reported. When reported, the incidence of abrasion/lacerations injuries varies from 0.8 to 6.1 injuries per 1000 player-hours. Wound assessment techniques such as the Skin Damage Area and Severity Index can be a valuable tool to obtain a more accurate estimation of the incidence and severity of acute skin injuries.

**Conclusion:** The use of protective equipment, a skin lubricant, or wet surface conditions has a positive effect on preventing abrasion-type injuries from artificial turf surfaces. The literature also shows that essential biomechanical information of the sliding event is lacking, such as how energy is transferred to the area of contact. From a clinical and histological perspective, there are strong indications that a sliding-induced skin lesion is caused by mechanical rather than thermal injury to the skin.

## Introduction

Soccer, with 265 million active players, is the most popular sport practiced worldwide and is still expanding in its popularity.<sup>1</sup> As the game's global popularity increases, the climate plays a greater part in limiting its development. In adverse weather conditions, the use of natural grass fields is limited, and athletic performance suffers. Current generations of artificial turf mirror the playing characteristics of natural grass and are resistant to inclement weather. The International Football Association Board (IFAB) has recognized the advances in artificial surface technology and decided to introduce artificial turf into the laws of the game in July 2004.<sup>2</sup>

From epidemiological injury studies, it can be concluded that the majority of football injuries (41 %-81 %) are caused by physical contact.<sup>3,4,5,6,7,8,9</sup> The physical contact is mainly attributed to player-to-player contact during tackling actions. Only Fuller et al separately reported the incidence rate of player-surface contact.<sup>6</sup> Of all reported injuries of male players, 6.6 % of those on artificial turf are from player-surface contact versus 7.5 % on natural grass.<sup>6</sup> Unfortunately, Fuller et al did not correlate the type of injury to this player-surface injury mechanism.<sup>6</sup> Until now, there are no published data available on the skin injury incidence rate caused by player-surface contact.

When player-surface contact involves too much energy, the skin is likely to fail, resulting in an abrasion.<sup>10</sup>

Acute skin injuries have been reported to be more common when playing on earlier generations of artificial turf.<sup>3,11</sup> In a more recent study, Ekstrand et al. concluded that burns and friction injuries caused by third-generation artificial turf pitches are not a problem anymore.<sup>12</sup>

On the other hand, interviews done by Yamaner et al. and the Royal Dutch Football Association (KNVB) showed that up to 84 % of players reported abrasions, indicating that these injuries are by far the most frequent type of injury when playing on artificial turf.<sup>13,14</sup> Yamaner et al. attribute these abrasion injuries to different conditions of playing fields.<sup>14</sup> Unfortunately, the different conditions were not described. Zanetti interviewed 1600 amateur players who generally judged the artificial turf better than natural grass, with the exception of the risk of abrasion by sliding tackles in 3 of the 8 investigated fields.<sup>15</sup> Although the injury incidence obtained from epidemiological research suggests otherwise, the perceived risks of abrasion and discomfort when playing on artificial turf calls for a deeper understanding of the acute skin injury mechanism due to player-surface contact.

The aim of this survey was 2-fold: (1) to gain insight into the incidence of reported skin injuries related to soccer and (2) to describe the skin injury mechanism due to player-surface contact.

## Materials and methods

The injury prevention model described by van Mechelen et al. was taken as the framework for this survey.<sup>16</sup> According to this model, the extent of the skin injury (incidence and severity) and mechanisms are the starting points to introduce preventive measures and assess its effectiveness. Different risk models for sport-related injuries have been proposed to study injury mechanisms.<sup>17,18,19,20</sup> The Bahr model combines the epidemiological model of Meeuwisse and the biomechanical perspective as described by McIntosh.<sup>19,20</sup> Furthermore, this model takes the characteristics of the sports into account. Bahr and Krosshaug combined internal risk factors related to the athlete, external risk factors, and the event leading to the injury.<sup>21</sup> This comprehensive model for injury causation was used to assess the risk factors for skin injuries caused by player-surface contact during soccer.

The PubMed database was searched using the keywords *injury*, *football*, and *artificial turf*. Inclusion criteria for this survey were provided as follows: (1) data about skin injury incidence and severity in combination with the applied injury definition and (2) possible epidemiology, mechanisms, and risk factors of skin injury related to player-surface contact in football. We used the following exclusion criteria: (1) unavailable in English or (2) skin injury data that we were unable to recalculate to suit this article.

Article reference lists and relevant Dutch publications were used as additional supportive articles. A further search was conducted using the keywords *wound definition and assessment*, *tackle*, and *fall studies* in combination with *sports* and *thermal skin injury* to find papers that described potentially relevant skin injury mechanisms related to player-surface contact in soccer.

### Skin injury definition and incidence

In the past, different definitions for injury were used, which make it difficult to compare results of injury incidence studies. Therefore, an Injury Consensus Group, under the auspices of the Fédération Internationale de Football Association Medical Assessment and Research Centre (F-MARC), produced a consensus statement.<sup>22</sup> According to this statement, an injury is defined as

*any physical complaint sustained by a player that results from a football match or football training, irrespective of the need for medical attention or time loss from football activities. An injury that results in receiving medical attention is referred as a "medical attention" injury, and an injury that results in a player being unable to take full part in a future football training or match as a "time loss" injury.*<sup>22 (p123)</sup>

Furthermore, this statement contains categories for classifying the type of injury. According to this statement, contusions are considered as a separate class of skin injuries compared with lacerations and abrasions. Unfortunately, definitions of these types of skin injuries are not included in the statement. An overview of the definitions and appearance of the relevant acute skin injuries described in literature are summarized in Table 1.

**Table 1** Overview of definitions and clinical appearance of soccer-related acute skin injuries.

Skin injury	Reference	Definition	Appearance
Abrasion	Basler et al. <sup>10</sup>	Superficial removal of the granular and keratinized cells from the underlying dermis, produced by acute contact of exposed skin with the immediate environment	Irregularly denuded epidermis and an exposed upper dermis with punctate bleeding and tissue exudate
Turf burn	Basler et al. <sup>10</sup> , Metelitsa et al. <sup>23</sup>	Injury that is part abrasion and part burn due to the friction heat as result of a sliding contact of uncovered areas with artificially surfaced fields	Superficial abrasion
Contusion	Jennett <sup>24</sup>	Result of direct contact or blunt force without the skin being broken	If superficial, will result in visible bruising. If deep, a hematoma will develop within the affected tissue
Laceration	Miller-Keane and O'Toole <sup>25</sup>	Wound produced by the tearing of body tissue. External lacerations may be caused in many ways, such as a blow from a blunt instrument, a fall against a rough surface, or an accident with machinery	A cut or incision

As stated in the review study of Junge et al., the injury definition directly influences data collection and thereby the reported incidence of skin injuries.<sup>26</sup> If duration of time loss is taken as the only criterion, minor injuries and injuries “cured” by analgesics or other medications will be neglected, and the incidence of injury will be underestimated.<sup>26</sup> This is known as the “tip of the iceberg” phenomenon.<sup>16</sup> As an example, when the incidence of skin injury using time loss injury criteria is compared with medical attention criteria (Table 2), the incidence of abrasions and lacerations using time varies between 0.4 to 1.81 injuries per 1000 player-hours. However, with the medical attention definition alone, abrasions and lacerations are more frequently reported, varying from 0.8 to 6.1 injuries per 1000 player-hours. The differences in contusion incidence are even greater than lacerations and other skin injuries. Only Fuller et al. found a significant difference between artificial turf and natural grass during soccer matches with male players.<sup>6</sup> More skin injuries were reported on artificial turf compared with natural grass.<sup>6</sup> No significant differences of incidence of skin injuries were found between surface and sex in other studies.

**Table 2** Skin injury rate of different types of skin injuries depending on sex and playing surface using time loss and medical attention as injury definition.

Study	Injury definition	Type of skin injury
Fuller et al. <sup>6,7</sup>	Time loss	Laceration/skin lesion
Ekstrand et al. <sup>27c</sup>	Time loss	Laceration/abrasion
Ekstrand et al. <sup>12</sup>	Time loss	Skin lesion
Hawkins and Fuller <sup>8c</sup>	Time loss	Laceration
Bjørneboe et al. <sup>28</sup>	Time loss	Laceration
Bjørneboe et al. <sup>28</sup>	Time loss	Contusion
Fuller et al. <sup>6</sup>	Time loss	Contusion
Arnason et al. <sup>29</sup>	Time loss	Contusion
Ekstrand et al. <sup>12</sup>	Time loss	Contusion
Ekstrand et al. <sup>27c</sup>	Time loss	Contusion
Hawkins and Fuller <sup>8c</sup>	Time loss	Contusion
Lindenfeld et al. <sup>30</sup>	Medical attention	Abrasion
Dvorak et al. <sup>31</sup>	Medical attention	Laceration
Junge et al. <sup>32c</sup>	Medical attention	Laceration
Aoki et al. <sup>33</sup>	Medical attention	Laceration/skin lesion
Kordi et al. <sup>9</sup>	Medical attention	Laceration/skin lesion
Fuller et al. <sup>34c</sup>	Medical attention	Laceration/abrasion
FIFA <sup>4c</sup>	Medical attention	Laceration/abrasion
Aoki et al. <sup>33</sup>	Medical attention	Contusion
Fuller et al. <sup>34c</sup>	Medical attention	Contusion
Dvorak et al. <sup>31c</sup>	Medical attention	Contusion
Junge et al. <sup>32c</sup>	Medical attention	Contusion
FIFA <sup>4</sup>	Medical attention	Contusion

<sup>a</sup> Data are expressed as number of incidences per 1000 hours of exposure.

– indicating that the specific incidence data were not described in the study.

<sup>b</sup>  $p < 0.01$ .

<sup>c</sup> Data in original articles were recalculated to suit the format.

Incidence of acute skin injury in matches (in training) <sup>a</sup>			
Males		Females	
Artificial Turf	Grass	Artificial turf	Grass
1.81 <sup>b</sup> (0.02)	0.61 <sup>b</sup> (0.04)	0.29 (0.04)	0.24 (0.02)
—	0.07	—	—
0.81 (0.06)	0.37 (0.07)	0.22 (0)	0 (0)
—	0.38 (0.03)	—	—
0.7	0.4	—	—
4.0 (0.3)	3.8 (0.2)	—	—
5.83 (0.53)	6.35 (0.53)	4.57 (0.28)	5.05 (0.23)
—	5.9 (0.50)	—	—
7.17 (0.70)	6.04 (0.46)	3.55 (0.32)	3.29 (0.29)
—	1.3	—	—
—	3.53 (0.27)	—	—
3.50	—	0.90	—
—	2.84	—	—
—	6.15	—	—
—	0.83	—	—
3.62	—	—	—
—	4.02	—	—
4.72	3.09	—	—
—	2.22	—	—
—	30.77	—	—
—	35.03	—	—
—	39.29	—	—
47.19	51.76	—	—

### Severity of traumatic skin injuries

The Injury Consensus Group has formulated the injury severity as follows: “The number of days that have elapsed from the date of injury to the date of the player returns to full participation in team training and availability for match selection.”<sup>22 (p193)</sup>

Studies that reported the severity of skin-related injuries are summarized in Table 3. These data indicate that skin injuries such as abrasion and laceration are mainly qualified as slight to minimal injuries, which seldom lead to long absence from training or matches.

The normal healing time of an acute skin injury, like an abrasion, is 3 weeks. During this period, inflammation, proliferation, and remodeling takes place.<sup>36,37</sup> It is likely that during the healing process, the skin lesion has an influence on playing behavior. Uncomfortable postures and movements will consciously or subconsciously be avoided.<sup>38</sup> However, this perceived discomfort and its effect on the football match have never been investigated. The number of sliding tackles performed during a match could be an indicator of altered player behavior depending on the playing surface. Based on video analysis, Andersson et al found a significantly lower number of sliding tackles on artificial turf compared with natural grass.<sup>39</sup> However, Wooster did not find significant differences when analyzing games played in the Union of European Football Associations (UEFA) Champions League and UEFA Cup.<sup>40</sup> The number of sliding tackles probably not only depends on the surface but also on other factors, like tactics and soccer skills.

Although the effects of skin trauma on participation seem minimal, skin injuries need proper treatment to prevent complications, in particular, infections.<sup>37,41,42</sup> Infections can be caused by fungi, viruses, and bacteria like methicillin-resistant *Staphylococcus aureus* (MRSA).<sup>43,44,45</sup> It must be emphasized that these infections are mainly spread by direct skin-to-skin contact, as reported for wrestling and American football. The risk of contamination due to playing surface–skin contact is low. McNitt and Petrunak described that, in general, the numbers of microbes present in synthetic turf are lower than natural grass.<sup>46</sup> The infectious *Staphylococcus aureus* bacterium was not found on any type of playing surface.<sup>46</sup>

### Skin injury mechanism due to player-surface contact

To describe the skin injury mechanism due to player-surface contact, the results of the literature search were categorized as intrinsic factors, extrinsic risk factors, and event according to the comprehensive injury causation model of Bahr and Krosshaug (Table 4).<sup>21</sup>

These results demonstrate that wet playing surfaces, protective equipment, and the use of a skin lubricant decreases the incidence of abrasion injuries. Conflicting results are reported with regard to the influence of age, gender, type of surface, behavior, position on the field, and level of performance on the incidence of skin injuries.

**Table 3** Injury severity classifications<sup>a</sup>.

Study	Type of Skin Injury	Total Reported Skin Injuries, %	Severity Classification, % <sup>b</sup>					
			Slight (<1)	Minimal (≥1)	Mild	Moderate	Severe	
Bargat <sup>35</sup>	Blisters/abrasion	100	90	10				
Junge et al. <sup>32c</sup>	Contusion	49	39	61				
	Laceration	8	85	15				
Dvorak et al. <sup>31c</sup>	Contusion	51	48	51				
	Laceration	5	83	17				
					(1-7)	(8-21)	(>21)	
Bjørneboe et al. <sup>28</sup>	Contusion	23			79	17	4	
	Laceration	2.5			80	16	4	
Arnason et al. <sup>29</sup>	Contusion	20			76	18	6	
			(1-3)	(4-7)	(8-28)	(8-28)	(>28)	
Ekstrand et al. <sup>12c</sup>	Contusion	17			41	38	19	2
	Laceration	1			32	35	32	
	Abrasion	0.2			43	43	14	

<sup>a</sup>Injury severity was classified according to the number of days a player was absent because of an acute skin injury. Percentages were calculated from total reported skin injury data.

<sup>b</sup>Severity definitions according to Ekstrand et al.<sup>12</sup> Values in parentheses indicate injury severity depending on the days of absence during training and match

<sup>c</sup>Data in original articles were recalculated to suit the format.

**Table 4** Risk factors obtained from literature<sup>a</sup>.

Risk Factor	Study	Outcome
<b>Intrinsic factors</b>		
Gender	Bargar <sup>35</sup>	Male subjects sustained a greater frequency and higher rate of skin trauma than females during the competitive season played on artificial turf
Age	Bargar <sup>35</sup>	A decrease in the number of wounds as the age of the subject increased
	Akkaya et al. <sup>47</sup>	Soft tissue injuries (superficial tears and abrasions) were most frequently seen in adult cases compared with adolescents as a result of soccer injuries on synthetic fields. The most frequently injured sites were the lower extremities
Location	Immers <sup>48</sup>	On artificial turf, abrasion injuries mostly occur on knee (77 %) and upper leg (72 %) resulting from self-reports of players
<b>Extrinsic factors</b>		
Field condition/ coefficient of friction	Immers <sup>48</sup>	Perceived less abrasion injuries (82 % of population) on wet artificial turf.
	Verhelst et al. <sup>49</sup>	The temperature rise measured with the novel sliding tester of a third-generation football field with sand and rubber infill in wet conditions (2 °C) is much smaller than in dry condition (8 °C)
	Sanchis et al. <sup>50</sup>	The correlation between the coefficient of friction and the roughness increase due to damage of a silicone skin replacer is not good. There is, however, a good correlation between human perception and the damaged artificial skin
Type of surface	Ekstrand et al. <sup>12</sup>	No significant differences were found in skin lesions between grass and third-generation artificial turf
	Fuller et al. <sup>6</sup>	Laceration/skin lesions in men were reported significantly higher on artificial turf than on grass ( $p < 0.01$ ) in matches
	FIFA <sup>4</sup>	The incidence of laceration/abrasion injuries between natural grass (3.09 injuries/1000 playing-hours) and football turf (4.72 injuries/1000 playing-hours) are comparable
	Immers <sup>48</sup>	The average annually self-reported number of abrasion injuries per player on artificial turf is twice as high than on natural grass (7.44 vs 3.14)
	Kordi et al. <sup>9</sup>	The incidence of laceration/skin lesions during match are significantly higher ( $p < 0.01$ ) when played on dirt fields compared with artificial turf (16.34 vs 3.62 skin injuries/1000 playing-hours)

**Table 4** Continued.

Risk Factor	Study	Outcome
<b>Extrinsic factors</b>		
	Hoekman and van den Heuvel <sup>13</sup>	68 % of the participants have experienced abrasion-type injuries when playing on artificial turf
	Zanetti <sup>15</sup>	Styrene-butadiene rubber infill material is preferred by all player roles with respect to skin abrasion on artificial turf pitches
	Peppelman et al. <sup>51</sup>	Sliding on natural grass results in more erythema but less abrasions compared with sliding on artificial turf
Skin product	Immers <sup>48</sup>	The use of a lubricant skin product reduces the temperature rise of a skin replacer in sliding contact with artificial turf significantly
Protective equipment	Basler et al. <sup>52</sup>	Protective equipment such as sliding pads, long-sleeve shirts, long socks, "biker" shorts, or self-adhesive bandage applied on skin areas that may potentially receive trauma can prevent skin abrasions
<b>Event</b>		
Player behavior	Andersson et al. <sup>39</sup>	The number of sliding tackles per match performed on artificial turf was markedly lower ( $p < 0.05$ ) than on natural grass ( $2.1 \pm 0.5$ vs $4.3 \pm 0.6$ )
	Wooster <sup>40</sup>	From a comparative performance analysis of games played in UEFA Champions League and UEFA Cup, the number of tackles performed on grass and football turf are comparable
Position	Bargar <sup>35</sup>	Midfielders are reported to suffer the majority of skin trauma, followed by defenders, forwards, and goalkeepers
	Yamaner et al. <sup>14</sup>	85 % of the goalkeepers and 83 % of the defenders complain the most of suffering abrasion injuries. In comparison, 64 % of the midfielders and 77 % of the forward players self-reported to suffer abrasion injuries
Activity	Bargar <sup>35</sup>	Higher frequency of skin trauma in practice than in competition on artificial turf
	Fuller et al. <sup>6,7</sup>	The incidence of laceration/skin lesions during training (0.02/0.04 injuries/1000 playing-hours) is significantly lower than during match (1.81/0.61 injuries/1000 playing-hours) both on grass and on artificial turf
Tackle/ action	Basler et al. <sup>52</sup>	Abrasion-type skin injuries are typically associated as a result of sliding contact with playing surfaces
	Fuller et al. <sup>53</sup>	Tackled players and tackling players were nearly 3 times as likely to suffer a contusion as a result of a tackle from the side than for a tackle from behind

**Table 4** Continued.

Risk Factor	Study	Outcome
Event		The incidence of abrasion/laceration injuries from a slide in tackle for a tackled and tackling player is 0.9 and 0.5 injuries/1000 tackles, respectively
		The incidence of contusion from a slide in tackle for a tackled or tackling player is 12.4 and 3.7 injuries/1000 tackles, respectively
	Tscholl et al. <sup>54</sup>	25 % of the observed tackles for male players are sliding tackle compared with 11 % for female players

<sup>a</sup>Data are organized according to the Bahr and Krosshaug model applied for acute skin injuries resulting from player-surface contact during soccer.<sup>21</sup>

## Discussion

Although skin injuries are uncomfortable and unpleasant, they seldom lead to absence from training or a soccer match. In addition, medical attention is not often needed.<sup>12,28,32,34,31</sup> The commonly used injury definition, which is mainly based on time loss or need for medical attention, determines data collection during incidence studies. Therefore, it is not surprising that abrasions and lacerations are not often reported. The reported incidence of these injuries varies from 0.8 to 6.1 per 1000 player-hours.<sup>4,6,7,8,9,12,28,30,31,33,34</sup> Retrospective studies in which players were questioned document that players sustained more abrasions than more severe injuries like strains, sprains, and fractures.<sup>13,14,15,48</sup>

The difference between injury surveillance and retrospective player perception studies is noteworthy because previous studies demonstrate that injury reporting is more reliable and does not suffer from recall bias.<sup>28</sup> The difference between player perception of skin injuries and the injury criteria indicate that the time loss or medical attention injury definitions are not sensitive and accurate enough.

Wound assessments, common in dermatological practice, could be of increased value.<sup>55,56</sup> These assessments examine all aspects of an injury. In this perspective, the newly developed scoring system to quantify sliding-induced skin lesions described by van den Eijnde et al. is of interest.<sup>57</sup> The Skin Damage Area and Severity Index (SDASI) is based on visual scaling of the clinical parameters abrasion, erythema, and exudation. The extent of the involved area complements the SDASI.<sup>57</sup> It must be noted that other new or additional methods of data collection could place greater time demands on the medical personnel involved in these studies.<sup>22</sup>

The model described by Bahr and Krosshaug<sup>8</sup> was used to address risk factors for acute skin injuries caused by player-surface contact. Based on this study, it can be concluded that there is consensus with regard to the positive effect of a wet surface condition and the use of protective equipment or skin lubricant. There are conflicting results regarding the influence of age, sex, type of surface, behavior, position on the field, and level of performance on the incidence of skin injuries. More important, this overview shows that there are multiple risk factors for abrasions, confirmed by Zanetti, who demonstrated that skin abrasions are influenced by the field configuration, role in the game, weather condition, and infill type.<sup>15</sup> For a third-generation artificial turf field, the infill consists of rubber granules, which are used as filling material between the grass artificial fibers.

According to Meeuwisse, the event itself is the main risk factor in acute injuries. External and/or internal risk factors contribute to a lesser extent to the cause of injury.<sup>20</sup>

A small contribution is required from other external and/or internal risk factors to cause an injury.<sup>20</sup> Few data are available in the literature on acute-type skin injury such as a sliding tackle. Only Fuller et al. compared the influence of tackle parameters to the propensity of injuries that required medical attention.<sup>53</sup> Unfortunately, only player-to-player contact injuries were recorded. The lack of description of the biomechanical factors associated with the sliding tackle is another more essential limitation of this study. In the field of biomechanics, McIntosh mentioned that injury analysis and prevention must explain how energy transfer arises, why it results in injury, and how it can be prevented.<sup>19</sup> Several biomechanical studies were performed in the field of football skills like kicking, heading, throw-in, running, and turning.<sup>58,59,60,61</sup> However, studies regarding the kinematics and energy transfer during a sliding tackle are lacking at the moment.

The types of biomechanical studies that are closely related to a sliding tackle are fall studies of walking or standing participants. Fall studies mainly focus on the risk factors of hip fracture and not skin injuries. Table 5 gives an overview of characteristic kinematic parameters such as vertical impact force and vertical impact velocity. Based on the findings of the study of Schmitt et al., an impact pressure value of approximately 110 to 125 Ncm<sup>-2</sup> (4000-4500 N) could result in a contusion.<sup>62</sup> Furthermore, it was demonstrated that the present literature lacks suitable values for contusion injury risk.<sup>58</sup> It is likely that the vertical kinematic parameters of a sliding tackle are comparable to a side jump of a goalkeeper. The horizontal initial speed of a sliding tackle even increases the total energy transfer during contact. Finally, the mechanical properties of the human skin, such as stiffness and ultimate strength, in combination with the physical condition of the skin determines how the skin will respond to physical loads during sliding.<sup>21</sup>

A more fundamental question with respect to energy transfer is whether skin damage is caused by mechanical or thermal injury due to friction, as the term *skin burn* suggests. Peppelman et al., in a histological study, found only removal of the stratum corneum.<sup>51</sup> The deeper skin tissue was undamaged. This suggests that a sliding tackle does not result

**Table 5** Characteristic kinematic parameters reported by different fall studies<sup>a</sup>.

Study	Type of experiment	Surface of impact	Side of impact	Body Mass Index, kgm <sup>2</sup>	Vertical impact force, N	Vertical i impact velocity, ms <sup>-1</sup>	Horizontal impact velocity, ms <sup>-1</sup>	Impact pressure, Ncm <sup>-2</sup>
Nankaku et al. <sup>63</sup>	Fall from standing height	Mattress	Hip	—	2251 ± 442.4	1.99 ± 0.32	—	—
Van den Kroonen-berg et al. <sup>64</sup>	Fall from standing height	Mattress	Hip	—	—	2.75 ± 0.42	—	—
Hsiao and Ronbinovitch <sup>65</sup>	Fall from standing height	Mattress	Pelvis	—	—	2.55 ± 0.85	—	—
Schmitt et al. <sup>58</sup>	Side jump by soccer goalkeepers	Foam layer	Hip	25 ± 1.0	5171 ± 1029	3.38 ± 0.42	2.71 ± 0.46	—
Schmitt et al. <sup>62</sup>	Side jump by soccer goalkeeper	Grass	Hip	25 ± 0.8	—	—	—	117 ± 54
Groen et al. <sup>66</sup>	Sideways falls of judokas	Judo canvas	Hip	21 ± 6.4 <sup>b</sup>	2579 ± 120 <sup>b</sup>	1.4 ± 0.1	—	—

<sup>a</sup>Values are expressed as mean ± standard deviation. A dash indicates that the specific kinematic parameter was not described in the study<sup>b</sup>Data in original articles were recalculated to suit the format.

in a deep dermal or full-thickness wound, which is characteristic for a deep second- or third-degree contact burn.<sup>67</sup> However in the same study, the expression of the thermal stress protein HSP70 was increased on both dry artificial and dry natural grass but not on water-sprinkled natural grass. Therefore, the concept of reversible superficial burns cannot be excluded at the moment. The surface temperature threshold at which irreversible epidermal injury occurs dependent on the contact time. The typical contact time of a sliding tackle is in the range of 1 second. The corresponding temperature threshold at which epidermal injury occurs is at least 60 °C.<sup>68</sup> A temperature rise of 8 °C, as measured by Verhelst et al. at 20 °C laboratory conditions, indicates that friction energy is not high enough to cause burns.<sup>49</sup> Furthermore, they reported that there was abrasion in dry conditions. This suggests that the skin failure mechanism caused by sliding is more mechanical than thermal. However, the environmental conditions are also important to take into account. It has been reported that the temperature of synthetic turf surfaces are significantly higher (35 °C to 60 °C) compared with natural grass surfaces when exposed to sunlight.<sup>69,70</sup> The temperature in the area of contact due to environmental conditions may be more important than the differences in sliding friction.

## Conclusion

Current injury surveillance lacks information about the incidence of acute skin injury. The development of a noninvasive, reliable technique to assess skin injury such as the SDASI may help obtain a more accurate estimation of the incidence and severity of acute skin injuries.

Clinical and histological data indicate that under normal environmental conditions, sliding-induced skin injuries are mainly caused by mechanical failure instead of thermal injury to the skin. Consequently, *abrasion* would be the correct term for a sliding-induced skin injury rather than *turf burns*. The chance of a reversible superficial burn cannot be excluded. A sliding tackle can cause a burning feeling but not a deep burn wound. Sprinkling water on synthetic turf makes sliding more comfortable; whether this also has a significant effect on the injury incidence has not been determined.

From this literature survey, it can be concluded that essential biomechanical information of a sliding tackle is lacking. A first step for future research is to quantitatively describe the kinematic parameters of a sliding tackle. These parameters are the boundary conditions for the mechanical stress to which the skin and body are exposed.

Finally, together with a sufficiently sensitive skin injury assessment method, multifactorial studies are necessary to identify the critical risk factors that contribute to a sliding-induced skin injury.

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# 2.2

## Identifying predictors of players' perception regarding sliding friendliness and the overall field performance of artificial turf systems for soccer

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## Abstract

Due to different design parameters, there is a large variety of artificial turf configurations on the market for soccer. The ultimate aim for any player surface is to maximize the performance and to minimize injuries. The aim of this study is to develop and validate the Football Turf Performance Questionnaire which measures the performance of an artificial turf soccer pitch and to identify predictors for both the overall performance and sliding friendliness based on the players' perceptions.

Three types of artificial turf configurations were evaluated by an elite soccer team in five different trials. Statistical analyses were performed to check the reliability, the classification into factors and identification of predictors, respectively.

The best predictors of the total judgment are: the descriptors "hardness of the field during falling and during sprinting" and "traction during stopping", and the indicators "traction" and "shock absorption". For sliding friendliness solely, the best predictors are: the descriptor "burning feeling of the skin after a sliding movement" and the indicators "skin irritation" and "traction".

## Introduction

Two decades ago, third-generation artificial turf surfaces were introduced in soccer. These new artificial playing surfaces consist of a multilayered construction in which performance characteristics can be designed according to the demands of the sports player. Partly due to the benefits over grass, such as low maintenance costs and high playing intensity and consistency, but also due to the acceptance into the laws of the game, artificial turf surfaces are globally gaining popularity.<sup>1</sup>

From the players' perspectives, the ultimate aim for any playing surface is to maximize performance and comfort, and to minimize injury and the risk of injury.<sup>2</sup> It is a challenge of sports engineering and biomechanics to determine where the limit should lie in improving performance without posing unacceptable risks to the player. Quasi-static and dynamic analyses of soils, for example, are used to determine the damping and traction of natural turf sports surfaces.<sup>3,4</sup> Both excessive traction and impact forces are factors considered to be associated with comfort and cause of injury.<sup>5</sup> In order to gain knowledge on the user safety of artificial turf, many studies have been performed by biomedical researchers, mainly focusing on the comparison with natural grass.<sup>6,7,8,9</sup> The outcomes have led to the FIFA Quality Concept For Football Turf in 2012 in which the main objective is to guarantee safe and reliable football turf pitches.<sup>10</sup> This FIFA quality procedure is based on instrumental testing, with respect to durability, ball-surface interaction and player-surface interaction.

Besides mechanical tests, the players' perceptions are of value to improve the understanding of the player-surface interaction. Biomechanical studies have shown that the interface properties directly influence the response of the human body during activities.<sup>11,12</sup> Many biomechanical studies regarding injury prevention have been done in the field of player-surface interaction, and in particular, regarding shock absorption and traction.<sup>13,14,15</sup> In contrast, subject studies related to sliding movement are rare, and insight in the injury mechanism is currently lacking.<sup>16,17</sup> Although frequently reported as discomfort by the player, skin injuries rarely lead to absence of training or matches, and therefore are classified as a moderate type of injury.<sup>18, 19</sup>

Due to different design parameters, there is a large variety of artificial turf configurations on the market. In a recent global study, players actually experienced this variability in surface properties. When players experienced differences between soccer turf pitches, players tended to assess artificial surfaces in comparison to natural grass as harder, more abrasive and providing less grip.<sup>20</sup> The mechanical heterogeneity within artificial turf systems not only influences the soccer players' perceptions, but also generates differences in physical performance. Sánchez-Sánchez et al. showed that the performance in sprinting and jumping are influenced by the mechanical parameters of traction, stiffness and force reduction of the artificial turf systems.<sup>21</sup>

In human-product interaction, (dis)comfort is a popular research topic with application in areas such as sitting, hand tools and running footwear.<sup>22,23,24</sup> Fleming et al. specifically

studied the players' perceptions of artificial sports surfaces for field hockey, since the player should be comfortable and confident with the surface.<sup>25</sup> After analysis, five important dimensions were derived, which determine the assessment of sports surfaces for field hockey by players. Player-surface interaction appeared to be one important dimension which contains three constructs: abrasiveness, hardness and grip. It is likely that these constructs are also applicable for soccer turf. The question is whether these constructs are predictors for sliding (dis)comfort in particular, or what we call sliding friendliness.

The aim of this study is to (1) develop and validate a psychometric instrument which measures the performance of an artificial turf pitch based on the players' perceptions and (2) to identify predictors for the overall judgement of the performance and sliding friendliness of artificial turf. These predictors could be essential during the whole lifecycle of an artificial turf pitch, from the early design process to the installation and use, respectively addressing product requirements and monitoring of pitches with respect to players' satisfaction and safety.

## Materials and methods

Three different types of artificial turf systems were evaluated by an elite soccer team in five different trials between April 2008 and April 2013. During each trial, a system was evaluated by a minimum of eighteen players. Systems 2 and 3 were the successive pitches upon which the elite soccer team played their home matches. System 1 was chosen as a reference. The pitches of systems 2 and 3 were assessed twice, immediately after installation and a half-year after installation, to measure the players' perceptions in time. Compared to system 1, systems 2 and 3 had the same use intensity and level of maintenance. The pitches differ in infill type (material and morphology), applied grass yarns (tape-monofilament vs monofilament combinations) and manufacturing of the top layer (tufted versus woven). Woven artificial turf is based on a double-face weaving process. The process of weaving brings advantages with regard to reduced production costs, and better product performance with regard to better pile fixation and upright positioning. A summary of the specifications of the evaluated artificial turf systems is presented in Table 1. All pitches were FIFA 2 star approved.<sup>10</sup>

In total, eighty-six different male professional soccer players from one club of the Dutch premier league participated in this study, which play their home matches on artificial turf. A minority of the players participated repeatedly in the study: namely, nineteen players twice and two players three times. Players of different playing positions were equally represented, including goal keepers. The mean age of these participants was 24.6 (19-38) years. The study was approved by the local ethics committee and the study was conducted in agreement with the Declaration of Helsinki principles. The players gave written informed consent to participate in the study.

**Table 1** Characteristics of the assessed artificial turf systems.

Characteristics	System 1	System 2	System 3
Top layer	tufted	tufted	Woven MX
<i>Fibre</i>			
Fibre material	Polyethylene	Polyethylene	Polyethylene
Fibre type	Tape	Monofilament/ tape	Monofilament combinations
Pile height [mm]	45	47	45
dTex/tuft settings	11600/2 15st - 5/8"	16000/8 & 5800/1 15st - 5/8"	6000/3 & 13200/6 & 12000/6
<i>Infill</i>			
Sand material	Round	Round	Round
Granulometry [mm]	0.5 - 1.0	0.5 - 1.0	0.5 - 1.0
Bulk density [g/cm <sup>3</sup> ]	1.4 - 1.6	1.4 - 1.6	1.4 - 1.6
Quantity [mm]	15	15	15
Rubber material	TPE Terra XPS	TPE – I-smart	TPE – I-smart
Granulometry [mm]	-	0.5-2.0	0.5-2.0
Bulk density [kg/m <sup>2</sup> ]	-	0.38	0.38
Quantity [mm]	7	14	14
<i>Support structure</i>			
Sub-base material	Compacted gravel	Compacted gravel	Compacted gravel
Elastic layer	Yes	Yes	Yes
Elastic layer thickness [mm]	10	14	12

The Football Turf Performance Questionnaire (FTPQ), which is used to assess the different pitches, is based on the FIFA Quality Concept for Football Turf.<sup>10</sup> The questionnaire consisted of two sections, with the aim to measure the field performance by means of Football Turf Performance Indicators (FTPI) and Football Turf Performance Descriptors (FTPD). The FTPI, comprising the main player-surface and ball-surface interaction parameters of the FIFA Quality Concept, are evaluated on an 11-point hedonic scale ranging from 0 (very bad) to 10 (very good), which corresponds to a student report rating. The aesthetic performance indicator is included later in the study, during trials 4 and 5. The FTPD are directly related to the FTPIs and refer to common actions during training and matches. The performance descriptors cover both player-surface and ball-surface actions and are based on literature and interviews with players and medical staff.<sup>25,26,27</sup> The

descriptors are related to product attributes and are scored on a 5-point analytical Likert scale with sensorial labels. The descriptors related to skin irritation and sliding friendliness are based on clinical parameters described by Peppelman et al.<sup>28</sup> The FTPIs and underlying FTPDs are summarized in more detail in the left column of Table 4. Finally, the overall performance is evaluated on an 11-point hedonic scale ranging from 0 (very bad) to 10 (very good), which corresponds to a student report rating.

The evaluations took place immediately after a two-hour routine training session. The training sessions were performed under dry weather conditions and temperature ranges between 11 to 21 degrees Celsius.

Analyses were performed with IBM SPSS 23.0 for Windows (IBM Corp. Armonk, NY). First, the Cronbach's alphas are derived to check the internal consistency of the FTPQ scaling. The test-retest reliability of the FTPQ is investigated when comparing the results of the FTPIs of trials 4 and 5 because a majority of these players participated in both trials. As a reference, instrumental measurements according to the FIFA Quality Concept for Football turf were performed on system 3 during the indicated time interval. These results were also involved in the analysis of variance.

The validity of the FTPQ is investigated by the ability to detect differences between artificial turf systems. Therefore, analysis of variance and a Tukey multiple-comparison test between the FTPIs and the different turf systems were performed. A Principal Component Analysis (PCA) with varimax rotation was performed to classify both the FTPD and FTPI into meaningful underlying factors.<sup>29</sup> The resulting major factors (eigenvalues > 1) are used to check the relationship between the FTPI and FTPD. Finally, a multiple regression (forward-selection procedure) was used to identify which of the FTPD and FTPI are predictors for the overall judgement and the perceived sliding friendliness.

## Results

Cronbach's alphas of the reliability check showed that the FTPIs and their underlying FTPDs have a high internal consistency ( $\alpha = 0.55 - 0.89$ ) and measures the overall performance of the pitch ( $\alpha = 0.77$ ).<sup>30</sup> Of note is that the consistency of the sliding friendliness indicator ( $\alpha = 0.55$ ) with the descriptor "feeling of gliding" is poor. Excluding this descriptor leads to a considerable increase in consistency of the sliding friendliness indicator ( $\alpha = 0.68$ ).

The test-retest reliability of the FTPQ is investigated when comparing the results of the FTPIs of trials 4 and 5, which were performed within a half-year time frame. From the results of the analysis of variance, shown in Table 2, no significant differences were found between the FTPIs. Instrumental measurements were performed to check possible changes of the surface characteristics between the two trials. Except for the results of the shock absorption, no significant differences were found.

**Table 2** Characteristics of the assessed artificial turf systems.

	Trial		F	p	
	4	5			
<b>system</b>	3	3			
<b>data</b>	Nov-12	Apr-13			
<b>temperature</b>	9	15			
<b>number of subjects</b>	20	24			
FTPI1 Traction	6.35 ± 1.09	6.25 ± 1.51	0.147	0.884	5-4*
FTPI2 Shock absorption	6.15 ± 1.50	6.00 ± 1.32	0.089	0.930	5-4
FTPI3 Stability	6.35 ± 1.09	6.42 ± 0.93	-0.252	0.802	4-5
FTPI4 Sliding friendliness	5.43 ± 1.45	5.37 ± 1.34	0.086	0.932	5-4
FTPI5 Skin irritation	6.43 ± 1.99	6.32 ± 1.77	0.129	0.898	5-4
FTPI6 Ball behaviour	5.80 ± 1.79	5.79 ± 1.14	-0.009	0.993	5-4
FTPI7 Aesthetic	7.80 ± 1.20	7.46 ± 1.28	0.785	0.437	5-4
Overall judgement	6.00 ± 1.63	6.17 ± 1.20	-0.793	0.432	4-5
FIFA 02 Vertical ball rebound [cm]	84 ± 1	83 ± 2	0.400	0.561	5-4
FIFA 03 Ball roll [m]	5.7 ± 0.2	5.5 ± 0.3	0.400	0.561	5-4
FIFA 04 Shock absorption [%]	67.4 ± 0.76	64.4 ± 0.67	22.118	0.009	5/4
FIFA 05 Vertical deformation [mm]	9.72 ± 0.27	9.63 ± 0.20	0.188	0.687	5-4
FIFA 06 Rotational resistance [Nm]	40.4 ± 1.45	40.7 ± 1.21	0.060	0.819	4-5
* Trials separated with "/" are significantly different. Trials separated with "-" are not significantly different at the 0.05 level					

The results of the analysis of variance and Tukey multiple-comparison test between the different turf systems with respect to overall performance and FTPIs are shown in Table 3. On all performance indicators, turf system 1 significantly has the lowest score, resulting in the significantly lowest overall performance score of the three systems ( $F = 27.40$ ,  $p < 0.01$ ). Turf system 2 has the highest score with regard to stability and ball behaviour, resulting in the significantly highest overall performance score. This analysis showed that the FTPQ is able to discriminate between turf systems, which is an important characteristic of validity.

Seven major factors (Eigenvalues  $> 1$ ) were revealed by PCA, explaining 82.4 % of the variance. The first four factors are predominant, since the scree plot showed a sharp decrease in Eigenvalues after the fourth factor. The correlation coefficients between the factor scores of the seven factors from the PCA are shown in Table 4. The factors were

**Table 3** Analysis of variance and multiple-comparison results of the Football Turf Performance Indicators (FTPIs) and the different turf systems (mean  $\pm$  standard deviation).

	System			F	p	
	1	2	3			
<b>Number of subjects</b>	22	45	44			
FTPI1 Traction	5.48 $\pm$ 1.47	6.80 $\pm$ 1.23	6.30 $\pm$ 1.34	7.091	0.001	1/2-3*
FTPI2 Shock absorption	2.73 $\pm$ 1.61	6.53 $\pm$ 1.16	6.08 $\pm$ 1.44	61.471	0.000	1/2-3
FTPI3 Stability	5.05 $\pm$ 1.43	6.96 $\pm$ 1.19	6.35 $\pm$ 0.98	19.751	0.000	1/3/2
FTPI4 Sliding friendliness	2.69 $\pm$ 1.44	5.89 $\pm$ 2.28	5.57 $\pm$ 1.25	15.432	0.000	1/2-3
FTPI5 Skin irritation	3.08 $\pm$ 2.18	5.78 $\pm$ 2.60	6.47 $\pm$ 1.74	10.625	0.000	1/2-3
FTPI6 Ball behaviour	4.90 $\pm$ 1.00	7.05 $\pm$ 1.10	5.78 $\pm$ 1.53	23.021	0.000	1/3/2
Overall judgement	4.00 $\pm$ 1.45	6.89 $\pm$ 1.57	6.05 $\pm$ 1.45	27.401	0.000	1/3/2

\* Turf systems separated with "/" are significantly different. Turf systems separated with "-" are not significantly different at the 0.05 level

labelled as follows: 1: traction; 2: sliding discomfort; 3: shock absorption; 4: kicking of the ball (shooting and passing of the ball); 5: ball dynamics (ball roll, ball speed and dribbling with the ball); 6: gliding contact; and 7: ball bounce.

Checking the linearity of the descriptors with respect to the dependent variables' overall judgement and the sliding friendliness judgement led to the exclusion of descriptors. Multiple regression analysis was performed on the reduced dataset.

Tables 5 and 6 show the results of the multiple regression analysis of the FTPDs and FTPIs with the overall judgement and sliding friendliness, respectively. The FTPD and FTPI predicting the overall judgment and the sliding friendliness are presented. The best predictors for the overall performance are: the descriptors "hardness of the field during falling", "hardness of the field during sprinting" and "traction during stopping", and the indicators "traction" and "shock absorption". For sliding friendliness solely, the best predictors are: the descriptor "burning feeling of the skin after a sliding movement" and the indicators "skin irritation" and "traction".

**Table 4** Factor loadings of the descriptors (FTPDs) and performance indicators (FTPIs) according to the PCA: factor 1 (traction), factor 2 (sliding discomfort), factor 3 (shock absorption), factor 4 (kicking of the ball), factor 5 (ball dynamics), factor 6 (gliding contact) and factor 7 (ball bounce).

	Factor						
	1	2	3	4	5	6	7
<b>FTPI1 Traction</b>	<b>0.749</b>	<b>-0.066</b>	<b>0.436</b>	<b>-0.094</b>	<b>0.305</b>	<b>0.117</b>	<b>0.033</b>
FTPD1 Traction during starting	0.780	-0.077	0.191	-0.128	0.168	0.327	-0.110
FTPD2 Traction during stopping	0.758	-0.051	0.244	0.060	0.185	0.016	-0.029
FTPD3 Traction during sidestepping	0.795	-0.067	0.229	0.047	0.074	-0.152	0.053
FTPD4 Traction during pivoting	0.794	0.006	0.184	0.044	-0.044	0.005	0.346
<b>FTPI2 Shock absorption</b>	<b>0.401</b>	<b>-0.218</b>	<b>0.803</b>	<b>-0.103</b>	<b>0.188</b>	<b>0.035</b>	<b>0.102</b>
FTPD5 Hardness during walking	-0.288	-0.005	-0.830	-0.223	-0.265	-0.080	0.140
FTPD6 Hardness during sprinting	-0.327	0.142	-0.777	0.334	-0.066	0.042	0.034
FTPD7 Hardness during falling	-0.506	0.623	-0.421	0.076	-0.117	-0.070	-0.031
FTPD8 Hardness during jumping	-0.337	0.280	-0.808	-0.128	0.043	-0.009	-0.125
<b>FTPI3 Stability</b>	<b>0.532</b>	<b>-0.079</b>	<b>0.468</b>	<b>-0.287</b>	<b>0.250</b>	<b>0.098</b>	<b>0.253</b>
<b>FTPI4 Sliding friendliness</b>	<b>0.168</b>	<b>-0.733</b>	<b>0.053</b>	<b>0.125</b>	<b>0.376</b>	<b>-0.169</b>	<b>0.156</b>
FTPD9 Gliding feeling during sliding movement	-0.005	0.402	-0.036	-0.045	0.369	0.724	0.135
FTPD10 Cutting feeling during sliding movement	0.142	0.590	-0.117	0.270	-0.019	0.568	-0.020
FTPD11 Abrasive feeling during sliding movement	-0.050	0.840	-0.114	0.184	-0.051	0.093	0.143
<b>FTPI5 Skin irritation</b>	<b>-0.198</b>	<b>-0.108</b>	<b>-0.054</b>	<b>0.461</b>	<b>.161</b>	<b>-0.782</b>	<b>0.156</b>
FTPD 12 Reddened skin after sliding movement	0.127	0.691	-0.160	-0.012	0.063	0.166	-0.530
FTPD 13 Burning feeling after sliding movement	-0.064	0.863	-0.123	-0.275	0.097	-0.032	-0.053
FTPD 14 Abraded skin after sliding movement	-0.257	0.558	0.146	-0.119	0.134	0.472	0.373

Table 4 Continued.

	Factor						
	1	2	3	4	5	6	7
<b>FTPI6 Ball behaviour</b>	<b>0.148</b>	<b>-0.229</b>	<b>0.329</b>	<b>-0.220</b>	<b>0.466</b>	<b>0.418</b>	<b>0.340</b>
FTPD15 Ball roll	0.326	-0.016	0.038	-0.411	0.744	-0.005	-0.050
FTPD16 Ball rebound	0.332	0.007	-0.082	-0.166	0.237	0.021	0.707
FTPD17 Ball speed	0.237	-0.161	0.134	-0.259	0.783	0.152	0.171
FTPD18 Dribbling with the ball	0.060	-0.158	0.274	-0.278	0.600	0.303	0.473
FTPD19 Shooting of the ball	-0.025	-0.077	0.076	0.929	-0.159	0.005	-0.137
FTPD20 Passing of the ball	-0.081	-0.114	-0.078	0.859	-0.365	-0.077	0.073
FTPD21 Chipping of the ball	0.158	0.144	-0.099	0.714	-0.122	-0.370	-0.289
<b>FTPI7 Aesthetic</b>	<b>0.115</b>	<b>0.314</b>	<b>0.518</b>	<b>-0.034</b>	<b>0.668</b>	<b>-0.167</b>	<b>0.082</b>

**Table 5** Results of the multiple regression analysis; unstandardized regression coefficients (beta) of the FTPD as predictors for the overall judgement of the surface performance and the perceived sliding friendliness together with the correlation coefficient R and coefficient of determination R square of the predictive model.

Dependent variable	Predictor	Beta	p	R	R <sup>2</sup>	Standard error
Overall Judgment	(constant)	7.44		0.85	0.72	1.03
	Hardness of the field during falling	-0.48	<0.01			
	Traction during stopping	0.47	<0.01			
	Contact with the ball during dribbling	0.34	<0.05			
	Hardness of the field during sprinting	-0.49	<0.01			
	Redness of the skin after a sliding movement	-0.26	<0.05			
Sliding friendliness	(constant)	7.47		0.81	0.66	1.27
	Burning feeling of the skin after a sliding movement	-1.21	<0.01			
	Contact with the ball during dribbling	0.64	<0.01			

## Discussion

This study shows that the proposed questionnaire, the FTPQ, is an adequate and valid method to measure performance of an artificial turf pitch. Analysis of players' perceptions by means of the FTPQ reveals that the best predictors of the total judgment are: the descriptors "hardness of the field during falling", "hardness of the field during sprinting" and "traction during stopping", and the indicators "traction" and "shock absorption". For sliding friendliness solely, the best predictors are: the descriptor "burning feeling of the skin after a sliding movement" and the indicators "skin irritation" and "traction". All of these had the expected signs. "Traction" ( $r=0.75$ ), "sliding friendliness" ( $r=-0.73$ ) and "shock absorption" ( $r=0.80$ ) were the performance indicators which showed the highest consistency with the three most dominant factors out of seven identified factors (Table 4).

Regarding the indicators "traction" and "shock absorption", Kati et al. suggested that traction and hardness of the surfaces are related to the perceived loading and injury risk of players.<sup>31</sup> Whether consciously or unconsciously, this implies that safety considerations and risk-avoiding behaviour are important psychological drivers which players take into account when judging an artificial turf pitch. In agreement with existing literature,

**Table 6** Results of the multiple regression analysis; unstandardized regression coefficients (beta) of the FTPI as predictors for the overall judgment of the surface performance and the perceived sliding friendliness together with the correlation coefficient R and coefficient of determination R Square of the predictive model.

Dependent variable	Predictor	Beta	p	R	R <sup>2</sup>	Standard error
Overall Judgement	(constant)	-0.68		0.88	0.77	0.77
	Traction	0.49	<0.01			
	Shock absorption	0.36	<0.01			
	Ball behaviour	0.23	<0.05			
Sliding friendliness	(constant)	-1.67		0.79	0.63	1.34
	Skin irritation	0.45	<0.01			
	Traction	0.49	<0.01			
	Shock absorption	0.21	<0.05			

traction, stiffness and energy absorption are the main mechanical risk factors of playing surfaces.<sup>5,6</sup> It must be remarked that players were free to use their own footwear during the test. Although traction properties can differ between artificial turf systems and cleat configurations, McGhie et al. interestingly found in their biomechanical study that the traction coefficient remained almost identical across all shoe-surface combinations.<sup>32</sup> In contrast with mechanical measurements, this indicates that subjects are adjusting for undesirable traction conditions.

The identified factor “sliding discomfort” (Table 4) showed not only a strong correlation between the abrasive feeling during the sliding movement ( $r=0.84$ ) and skin injury parameters: abrasion ( $r=0.56$ ), redness ( $r=0.69$ ) and burning feeling ( $r=-0.86$ ), but also with the experienced hardness of the surface during falling ( $r=0.62$ ). The harder the surface is perceived during falling, the less sliding friendly an artificial turf pitch is evaluated. An explanation for this phenomenon could be that a harder surface is less capable of absorbing energy, i.e. more energy is transferred to the human body. The strong correlation between the skin injury parameters and the experienced sliding discomfort implicates that an injury screening assessment like the proposed Skin Damage Area and Severity Index (SDASI) can be useful as an indirect readout for sliding discomfort.<sup>33</sup>

Initially, the “ball behavior” indicator was proposed to describe all underlying ball-related descriptors, while the PCA divided this FTPI into three factors: namely, “kicking of the ball”, “ball dynamics” and “ball bounce”. Ronkainen et al. identified “ball interaction”,

which was considered to be the ball-surface interaction, as one of the three dimensions in elite players' perceptions of artificial turf pitches.<sup>34</sup> This dimension could be divided into three sub-themes, namely: "ball roll", "ball pace" (also referred to as speed and tempo) and "ball bounce". In our study, these sub-themes were categorized differently, since "ball roll" and "ball pace" seem to be included in the factor "ball dynamics", while "ball bounce" was considered as a separate factor. The "kicking of the ball" in our study is also considered by Ronkainen et al. as a separate item, although not related to surface-ball interaction but to the players' techniques.

Roberts et al. used the following eight pitch properties: hardness, bumpiness, surface pace, consistency, abrasiveness, grip, grass length and grass thickness.<sup>20</sup> The FTPQ includes all of these properties, except for the specific grass geometric properties length and thickness. Globally, a variety of geometric grass properties are used. Roberts et al. found in his study a significant correlation between grass thickness and variability of football turf pitches. Therefore, grass thickness and length are important design properties which have added value when included to the FTPQ as part of the aesthetics indicator.

The aging and degradation of artificial turf pitches has become more and more at the attention both of end-users and suppliers, due to the durability of performance and product lifetime. Complementary to instrumental measurements, the FTPQ is also capable of measuring the important components or system effects like hardness and friction, which are related to degradation according to the degradation model described by McLaren.<sup>35</sup> Whether degradation necessarily leads to decreasing sliding friendliness properties has yet to be seen. Due to compaction of the infill, the hardness is increased which, according to our discovered correlation ( $r=0.62$ ), has a negative effect on the sliding friendliness.<sup>36,37</sup> On the other hand, friction is reduced due to proliferation of moss and algae, fibre flattening and fibre fibrillation which could have a positive effect on the sliding friendliness.<sup>35</sup>

Besides aging, surface temperature has an influence on the mechanical properties of the artificial pitch. Charalambous et al. have shown that a cold surface (1.8 °C – 2.4 °C) is significantly harder and stiffer than a warm surface (14.5 °C – 15.2 °C).<sup>12</sup> In our study, no players' tests took place on cold surfaces. When performing artificial turf pitch evaluation studies, surface temperature is an important parameter to take into account.

Finally, our study shows that sliding friendliness correlates strongly to physically unpleasant feelings like "cutting" and "abrasion", and not to comfortable feelings such as "gliding". Hereby, the term sliding friendliness can more adequately be defined as sliding discomfort. When developing sliding friendly turf pitches, one's ultimate goal is to reach the state of absence of sliding discomfort.

## Conclusion

This study presents a validated and reliable questionnaire which measures both the relevant performance indicators as well as performance descriptors. This study also

provides performance descriptors and performance indicators that predict both the overall players' judgements and sliding friendliness of artificial turf pitches. The developed FTPQ and derived predictors can be used during the whole product lifecycle of an artificial turf pitch: from the early design process by addressing product requirements to the installation and use by evaluating and monitoring pitches with respect to players' satisfaction and safety.

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## Supplement: The Football Turf Performance Questionnaire

Please **circle** the number that corresponds with your opinion

### Part A: Traction & Shock Absorption

How do you rate the...						
	low					high
traction during..						
starting	1	2	3	4	5	
stopping	1	2	3	4	5	
side stepping	1	2	3	4	5	
pivoting	1	2	3	4	5	
hardness of the field during..	soft					hard
walking	1	2	3	4	5	
sprinting	1	2	3	4	5	
falling	1	2	3	4	5	
jumping	1	2	3	4	5	

How do you rate the....											
	very bad										very good
traction properties	0	1	2	3	4	5	6	7	8	9	10
shock absorption characteristics	0	1	2	3	4	5	6	7	8	9	10
stability	0	1	2	3	4	5	6	7	8	9	10

### Part B: Sliding friendliness

How do you rate the...						
	not at all					very clear
feeling during the sliding movement						
gliding feeling	1	2	3	4	5	
cutting feeling	1	2	3	4	5	
abrasive feeling	1	2	3	4	5	
skin condition after the sliding movement	not at all					very clear
reddened	1	2	3	4	5	
burning feeling	1	2	3	4	5	
abraded	1	2	3	4	5	

How do you rate the ....											
	very irritated					no irritation					
degree of skin irritation after training	0	1	2	3	4	5	6	7	8	9	10
	very bad					very good					
sliding friendliness	0	1	2	3	4	5	6	7	8	9	10

**Part C: Ball Behaviour**

How do you rate the...										
following ball characteristics										
	bumpy					smooth				
ball roll	1	2	3	4	5					
	low					high				
ball bounce	1	2	3	4	5					
ball velocity	1	2	3	4	5					
contact with the ball during..										
	rough					easy				
dribbling	1	2	3	4	5					
	easy					difficult				
kicking	1	2	3	4	5					
passing	1	2	3	4	5					
chipping	1	2	3	4	5					

How do you rate the ....											
	very bad					very good					
ball behaviour	0	1	2	3	4	5	6	7	8	9	10

**Part D: Visual Appearance**

How do you rate the ....											
	very bad					very good					
appearance of the field	0	1	2	3	4	5	6	7	8	9	10

**Part E: Overall Judgement**

How do you rate the ....											
	very bad					very good					
overall performance of the pitch	0	1	2	3	4	5	6	7	8	9	10





# 2.3

## The Potential of the skin as a readout system to test artificial turf systems: clinical and immunohistological effects of a sliding on natural grass and artificial turf

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## Abstract

The purpose of this study was to investigate the interaction of skin with natural grass and artificial turf at clinical, histological and immunohistochemical level. Therefore, 14 male volunteers performed slidings on dry natural grass, wet natural grass and artificial turf. Directly and 24 h after the sliding, a clinical picture and a 3-mm punch biopsy of the lesion were taken. Paraffin sections (6  $\mu\text{m}$ ) were hematoxylin-eosin stained. Immunohistochemistry was performed for CD3, hBD-2, K16, K10, Ki67 and HSP70. Clinically, a sliding performed on artificial turf caused less erythema but more abrasion compared to natural grass. At histological level, artificial turf or dry natural grass damaged the stratum corneum the most. Directly after the sliding, CD3, hBD-2, K16, K10, Ki67 and HSP70 expression was normal. 24 h after a sliding on artificial turf or dry natural grass, an increase of K16, hBD-2 and HSP70 expression was observed. In this pilot study it was not possible to clearly distinguish between skin damage induced by a sliding on artificial turf and natural grass. However, small differences at clinical and histological level seem to exist. This demonstrates the potential of the skin as readout system to evaluate artificial turf systems and mechanical skin damage.

## Introduction

Soccer, also known as football, is the most popular sport worldwide with approximately 200 million players.<sup>1,2,3</sup> Like other popular team sports such as ice hockey, handball, basketball and rugby, soccer is a sport with a relatively high risk of injury. Participation in this sport is still increasing, leading to an increasing frequency of injuries resulting in higher cost for treatment.<sup>4</sup> The incidence and characteristics of soccer injuries during soccer matches at amateur and toplevel are well documented.<sup>4,5</sup> However, skin lesions are rarely described. Severity and frequency are underestimated because an injury is generally defined as any physical complaint caused by soccer that lasted for more than 2 weeks or resulted in absence from a subsequent match or training session.<sup>3,6</sup> Although missing a match or training due to a skin injury is uncommon, the related discomfort can still negatively influence players' performance.

A sliding is commonly performed during a soccer match and results in redness (erythema) and abrasion of the skin. Such surface-related traumatic damage is usually a minor injury, but it can be serious if it covers a large area or when foreign materials becomes imbedded in the skin lesion. The effects of artificial turf and natural grass on surface-related traumatic injuries in soccer suggests that surfaces with artificial turf produce more abrasion injuries than surfaces with natural grass.<sup>5,7,8</sup> However, these descriptive studies are only performed in small groups. Playing on different types of surfaces has been suggested to cause difference in injury pattern and mechanism. Further, alternation between different types of playing surfaces is related to a higher injury risk.<sup>7</sup>

Artificial turf became used widespread for baseball and soccer in the United States and Canada in the 1970s, both in outdoor and indoor stadiums. In Europe, some soccer clubs installed artificial surfaces in the 1980s. During this period, artificial turf gained a bad reputation with fans and especially players, since this artificial turf caused more injuries than natural grass.<sup>9</sup> The use of artificial turf for soccer purposes was banned by FIFA, UEFA and many domestic associations. However, artificial turf systems could be very useful in regions of the world with a climate that makes growth of adequate natural grass difficult.<sup>9,10,11</sup> Therefore in the last decade, new artificial playing surfaces have been developed. Some of these surfaces were specifically designed for soccer. The basic construction of the latest generation soccer-specific artificial turf is a blend of grass-like fibres attached to a special backing containing a mix of sand and rubber brushes. This construction has proven to be the most favourable for soccer to date. These "next generation" surfaces are often virtually indistinguishable from natural grass when viewed from any distance. Besides, they are generally regarded as being about as safe to play on as a natural grass.<sup>9</sup> In Europe, UEFA has approved the use of these artificial pitches at national and club level since the 2005–2006 season. Therefore, it is possible that soccer matches are played on artificial turf in the Champions' League, UEFA Cup or qualifiers for the World Cup and European championships.<sup>10,11</sup>

Soccer injuries predominately affect the ankle, knee and muscles of the thigh and calf.<sup>2,4,5</sup> The incidence of these injuries on artificial turf compared to natural grass are therefore studied the most. However, to the best of our knowledge no studies have been performed that evaluate skin lesions after a sliding on natural grass and artificial turf. For this reason, we have conducted an open descriptive study to evaluate the clinical, histological and immunohistochemical effects of a sliding on different playing surfaces.

## Methods

### Skin samples

14 male healthy volunteers from the same soccer team were included in this study after giving written informed consent. All participants were active amateur soccer players. The age of the volunteers ranged from 18 to 25 years, with a mean age of 22 years. Their height varied between 178–192 cm and weight was between 71–94 kg resulting in a body mass index between 20–25. The skin type of the volunteers was type II or III (white skin). The volunteers were asked to perform a “standard sliding” 1–10 times on 3 different types of playing surfaces. The running distance before a sliding was equal in all volunteers. Further, all volunteers played soccer at the same level and were equally trained. Slidings on natural grass were carried out in the soccer stadium Amsterdam Arena, the Netherlands. Two grass conditions were tested. A dry playground with the stadium roof closed and the same playground after 3 min water sprinkling (standard procedure in advance of a soccer game). Slidings on artificial turf were performed indoors on a third generation artificial turf system. This was a grass carpet containing fibrillated LSR yarn. The grass piles had a length of 6 cm and as basis 2 cm infill sand (M4C) and on top 2 cm of granulated thermoplastic elastomer. The lesions caused by the sliding were clinically characterized in a subjective way by an experienced not blinded dermatologist directly after the sliding and 24 h later. For this purpose, a clinical picture was taken and a description was given about, the size of the lesion and the degree (mild, moderate, severe) of erythema and abrasion. This study was approved by the local medical ethics committee and was conducted according to the principles of the Declaration of Helsinki. The study meets the ethical standards of the journal.<sup>12</sup>

### Histology and immunohistochemistry

For histological evaluation by a dermatologist and a biologist, directly after the sliding and 24 h later 3-mm punch biopsies were taken under local anesthesia with 1 % Xylocain/Adrenalin. These biopsies were embedded in paraffin after 4 h fixation in formaldehyde. Paraffin sections (6 µm) were processed side-by-side and dewaxed with histosafe (Adams) followed by rehydration in decreasing concentrations of alcohol (100–50 %) and demineralized water. These sections were hematoxylin-eosin (HE) stained for assessment

of histopathological features. Furthermore, immunohistochemical (IHC) staining was performed with monoclonal antibodies specific for CD3 (1:500) clone F7.2.38, human beta defensin-2 (hBD-2) (1:10,000) clone ab9871 (Abcam, Cambridge, UK), cytokeratin 16 (1:500) clone LL025 (Monosan, Uden, Netherlands), cytokeratin 10 (1:5,000) clone RKSE60 (Monosan, Uden, Netherlands), Ki67 (1:50) clone MIB-1 (DAKO, Copenhagen, Denmark), and HSP70 (1:50,000) clone W27 (Santa Cruz, Santa Cruz, USA) together with a hematoxylin counter-staining.

The sections for the CD3, K10, K16, Ki67 and HSP70 staining were pre-treated with peroxidase block (DAKO, Copenhagen, Denmark) and the sections for hBD-2 with 20 % normal rabbit serum. For the CD3 immunostaining, the sections were antigen retrieved by boiling the sections in EDTA (pH 8.0, 0.5 % Tween) for 10 min. For K16 and Ki67, pre-treatment with peroxidase block was followed by boiling of the sections in a 10-mM citrate buffer solution (pH 6.0) (high-temperature microwave oven retrieval technique by Cattoretti et al. at 450 W in a microwave oven for approximately 10 min and left to cool for 45 min.<sup>13</sup> Sections for K10 staining were antigen retrieved by trypsinization with trypsin-CaCl<sub>2</sub> solution for 15 min at 37 °C. Afterwards, all sections were air dried and immersed in phosphate buffered saline (PBS). For all staining except hBD-2, this initial step was followed by incubation for 15 min with 1 % bovine serum albumin (Organon Technika, Boxtel, the Netherlands) in PBS. Next for all staining, overnight incubation with the primary antibody was performed. For CD3, K16, K10, Ki67 and HSP70, this step was followed by incubation with HRP anti-mouse Envision (DAKO, Copenhagen, Denmark) for 30 min. The sections for hBD-2 were incubated with rabbit anti goat IgG biotinylated Vectastain ABC-elite kit (Vector laboratories, Burlingame, USA). To detect CD3, hBD-2, K16, K10, Ki67 or HSP70, all sections were washed in PBS and visualized using 3,3' diaminobenzidine (DAB). Sections were counter-stained with Mayer's haematoxylin (Sigma, St Louis, USA) and after dehydration with 100 % ethanol and histosafe mounted in Permount (BDH chemical, Poole, England). Finally, the sections were photographed at a magnification of 20x using a microscope (Axioskop2 MOT; Zeiss), digital camera (Axiocam MRc5; Zeiss) and AxioVision software (Zeiss).

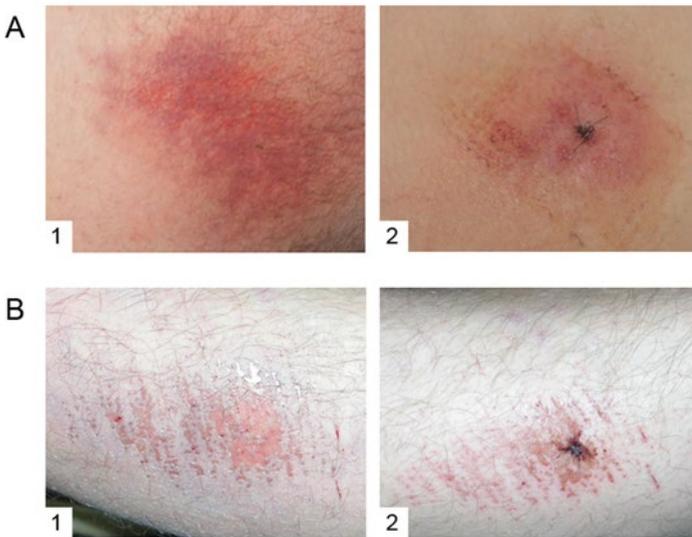
## Results

The aim of this study was to investigate the effect of a sliding on the skin, on natural grass and artificial turf. Therefore, the clinical appearance of skin lesions caused by a sliding is described. Directly after the sliding, the size of the skin lesions on the thigh of the volunteers caused by natural grass or artificial turf varied between 5–90 cm<sup>2</sup> and 20–70 cm<sup>2</sup>, respectively. All playing surfaces caused erythema of the skin, however based on the findings of a dermatologist a sliding on artificial turf resulted in milder erythema compared to dry and wet natural grass. In contrast, almost no abrasion was found after a sliding on

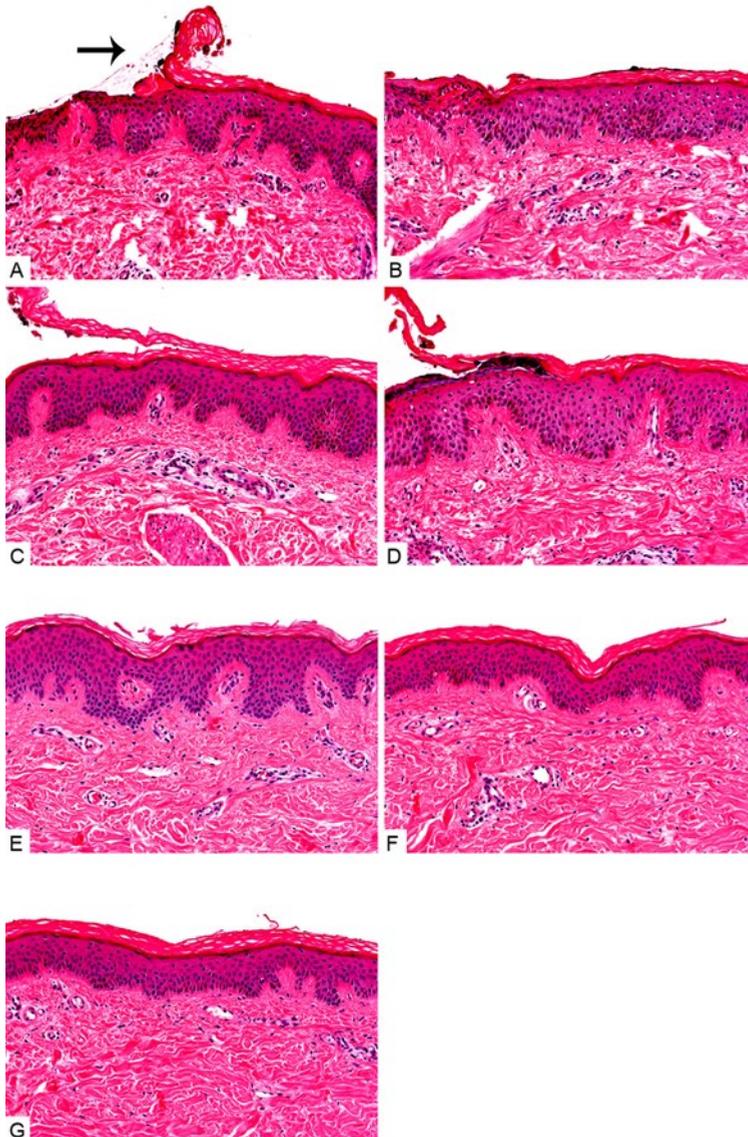
natural grass, which did appear after a sliding on artificial turf (Figure 1 and Table 1). Further, wet natural grass caused less erythema and abrasion compared to dry natural grass.

Almost all lesions were clinically improved 24 h after the sliding, which was illustrated by reduction of erythema (Figure 1 and Table 1). Inter-individual differences were observed in all groups. In addition to these observations, 2 aberrant cases were found. One of the volunteers who performed a sliding on artificial turf did not show any features of skin damage. In a second volunteer, an extreme inflammatory reaction accompanied by pinpoint bleedings was observed after a sliding on wet natural grass. Histology confirmed the clinical observations of these two cases. Overall, it seems that a sliding on natural grass results in more erythema but less abrasions compared to a sliding on artificial turf.

In addition to the clinical evaluation, HE and IHC stainings were performed to study histological changes in the skin lesions after a sliding on the tested playing surfaces. In 13 volunteers, a sliding resulted in total or partial removal of the stratum corneum. However compared to wet natural grass, artificial turf and dry natural grass disrupted the stratum corneum the most (Figure 2).



**Figure 1** Clinical appearance of skin lesions caused by a sliding. Representative clinical pictures of skin lesions on the thigh of the volunteers caused by a sliding on different playing surfaces. **A** Lesion as result of a sliding performed on dry natural grass directly (1) after a sliding and 24 h later (2), demonstrating severe erythema and mild abrasion and exudate. **B** Skin lesion as a result of a sliding on artificial turf directly (1) after the sliding and 24 h later (2), illustrating moderate abrasion and mild erythema and exudate. In the middle of both pictures **A2** and **B2**, a small wound with a stitch can be observed at the location where the 3-mm biopsy was taken.



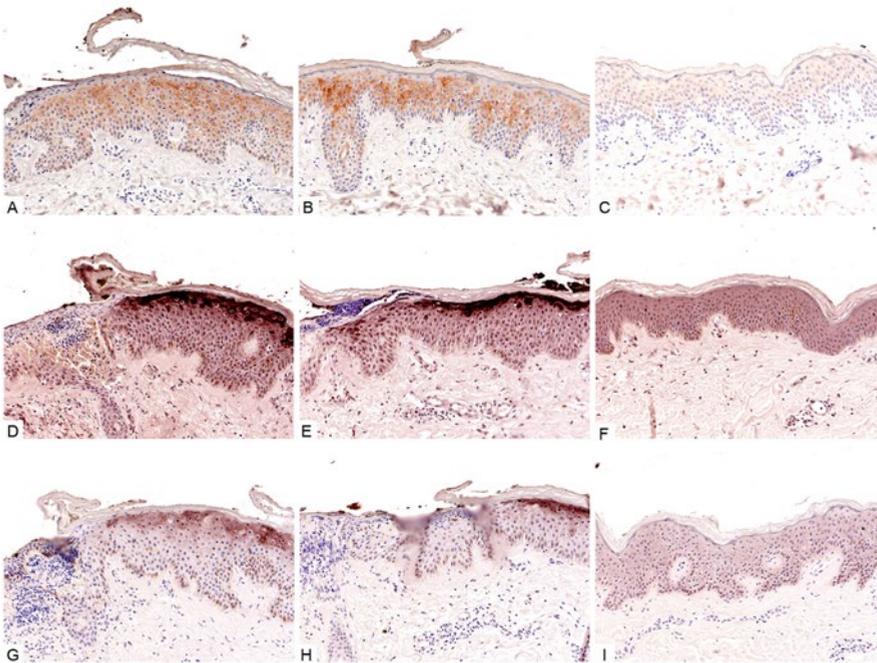
**Figure 2** Skin histology after a sliding on different playing surfaces. Representative pictures (20 × magnification) of HE stained skin biopsies after a sliding on 3 different playing surfaces. The columns consecutively represent the histology of the skin lesions directly after a sliding and 24 h later. **A, B** Skin histology after a sliding on artificial turf, illustrating removal of SC (black arrow). **C, D** Shows the skin after a sliding on dry natural grass, which results in removal of the SC (black arrows). **E, F** Demonstrates skin histology after a sliding on wet natural grass, showing less disruption of the SC compared to dry natural grass and artificial turf. **G** Normal skin histology.

Aberrant expression of CD3, hBD-2, K16, K10, Ki67 and HSP70 was not found directly after the sliding. Interestingly 24 h later, an increased epidermal K16 expression was observed as result of a sliding on artificial turf or dry natural grass ( Figures 3A-B). This K16 induction was not clearly accompanied by K10 reduction, which indicates mild disturbed epidermal differentiation.

In addition to changes in keratinocyte differentiation, a sliding induced epidermal thermal stress response and a component of the skin barrier function was studied by HSP70 and hBD-2, respectively. 24 h after a sliding on artificial turf and dry natural grass, suprabasal expression of HPS70 and hBD-2 was observed in 9 out of 10 volunteers, especially at areas with an undisrupted stratum corneum (Figures 3D, E, G, H). This increase of K16, hBD-2 and HSP70 expression within 24 h was not found in volunteers who performed a sliding on natural grass, indicating a normal epidermal differentiation, no thermal stress induction and a normal skin barrier function (Figures 3C, F, I). These observations correspond to the results of the HE staining. Further for all playing surfaces, infiltration of inflammatory cells and keratinocyte proliferation did not significantly increase 24 h after a sliding.

**Table 1** Overview of the scoring of erythema and abrasion (Scale: no ( - ), mild ( + ), moderate ( + + ), severe ( + + + )). The first column demonstrates the studied parameters and the measuring points. The second column represents the results of the volunteers who performed a sliding on dry (V1 t/m V4) or wet (V5 t/m V8) natural grass. The last column shows the results of the volunteers who performed a sliding on artificial turf.

Parameter		Natural grass								Artificial turf					
		V1	V2	V3	V4	V5	V6	V7	V8	V1	V2	V3	V4	V5	V6
Erythema	0h	++	++	+++	+	++	++	+++	++	+	+	+	-	+	-
	24h	+	+	++	+	+	+	++	+	-	+	-	-	+	-
Abrasion	0h	-	+	+	+	-	-	+	-	++	++	++	+	+	-
	24h	-	+	+	+	-	-	+	-	++	++	++	+	+	-



**Figure 3** Immunohistochemical staining of sliding damaged skin. The columns subsequently represent skin sections of sliding damaged skin 24 h after a sliding on artificial turf (**A, D, G**), dry natural grass (**B, E, H**) and wet natural grass (**C, F, I**). (**A–C**) K16 staining. There was an induction of K16 in both artificial turf and dry natural grass, which was not found in wet natural grass. (**D–F**) HSP70 staining. Suprabasal HSP70 expression was found after a sliding on artificial turf or dry natural grass but not after a sliding on wet natural grass. (**G, H**) hBD-2 staining. Increased hBD-2 expression was observed 24 h after a sliding on artificial turf or dry natural grass.

## Discussion

This study showed that there is no evidence of more skin related traumatic injuries when a sliding was performed on artificial turf compared to natural grass. This is in agreement with a study performed by Ekstrand et al. who investigated the risk of injury in elite soccer played on artificial turf vs. natural grass.<sup>9</sup> Both studies were carried out on improved third generation artificial turf, which is especially designed for soccer and has playing characteristics similar to natural grass. These artificial turf pitches were introduced in the late 1990s and are officially allowed by FIFA and UEFA for international matches.<sup>11</sup> We observed small differences between sliding damaged skin caused by wet natural grass, dry natural grass and artificial turf at clinical and histological level. This is in contrast

to the absence of a difference observed in the number of traumatic injuries. Based on our clinical findings, we confirm the suggestion by others that a sliding on natural grass results in more erythema but less abrasions compared to a sliding on artificial turf.<sup>4,5,11</sup>

At histological level, a sliding on artificial turf and dry natural grass reduced the skin barrier function within 24 h after the sliding. This was depicted by increased hBD-2 expression, which is known for its antimicrobial activity and can therefore be related to reduced skin barrier function.<sup>14,15</sup> In addition, this reduced skin barrier function is accompanied by thermal stress induction that is represented by HSP70. In inflammatory skin diseases with reduced skin barrier function like psoriasis and atopic dermatitis HSP70 is also involved.<sup>16</sup> In contrast, water sprinkling of natural grass seems to prevent this sliding induced thermal stress induction and skin damage. Therefore water sprinkling of natural grass before a soccer match seems to be a good approach in reducing soccer match related skin lesions and improvement of players comfort. This finding makes it interesting for future studies to evaluate the effect of water sprinkling of artificial turf on the incidence and severity of soccer match related skin lesions. Further, in a larger study implementation of a tool to measure the amount of erythema and abrasion, for example Courage and Khazaka, could be beneficial. Wound, burns and friction injuries that effect skin comfort are more common in soccer matches on artificial turf compared to natural grass.<sup>7,9</sup> These features are mainly caused by a sliding but usually do not result in absence from training or soccer matches and are therefore not reported as a traumatic injury.<sup>6,9,10</sup>

Although a sliding does not result in a severe injury it still causes players discomfort. The impact of sliding related injuries on players discomfort may therefore be underestimated. So the observed differences may be important in studying users skin comfort. However, differences in sliding techniques or pain perception can influence the results. Previous studies only investigated severe soccer related injuries on natural grass versus artificial turf. They did not investigate skin damage and its influence on players discomfort on these surfaces. We showed that skin damage can be evaluated at both clinical and biological level. This illustrates that besides tribology, biology is of importance in the development of artificial turf systems and testing their users comfort. This invasive study therefore shows the potential of the skin as a read-out system for skin damage and contributes to the development of novel non-invasive in vivo imaging methods to study skin damage and skin-material interaction.

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# 2.4

## Psychosensorial assessment of skin damage caused by a sliding on artificial turf: The development and validation of a skin damage area and severity index

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## Abstract

**Objective:** Injury prevention is an important reason for the development of performance standards in football. Currently, there is no objective method available to classify sliding induced skin injuries, which includes the perceived sliding friendliness of football pitches. The purpose of this study was to develop a non-invasive method for quantification of the observed sliding induced skin damage and evaluate whether there is a correlation between the subjective perceived skin irritation and sliding friendliness.

**Study design:** Randomized controlled trial.

**Methods:** Previously obtained clinical images of sliding induced skin lesions were rated by a dermatologist on the degree of abrasion, erythema and type of exudation. To test the practical feasibility of a proposed Skin Damage Area and Severity Index (SDASI) to characterize sliding induced skin lesions, a randomized user trial with nine amateur football players was performed. The sliding friendliness of three different grades of infill materials were tested.

**Results:** The SDASI correlates both with the perceived skin irritation ( $r = -0.53$ ,  $p = 0.02$ ) and sliding friendliness ( $r = -0.58$ ,  $p = 0.01$ ).

Statistical analysis of the individual clinical scores showed that perception of skin irritation and sliding friendliness correlate very well with the degree of erythema and abrasion. However, these scores are independent of the size of the lesion and type of exudation. There was no statistical significant difference found between the three evaluated types of infill and their sliding performance.

**Conclusions:** This study demonstrated that the SDASI, which is a tool for quantification of a sliding induced skin lesion, correlates very well with the perceived skin irritation and the sliding friendliness.

## Introduction

Injury prevention is an important reason for the development of safety and performance standards for soccer pitches. The introduction of artificial soccer pitches and its continuous evolution sets new challenges to develop and improve standards for classification of soccer pitches in terms of quality, performance and safety standards. In the field of injury prevention, important work is performed by the Fédération Internationale de Football Association (FIFA) Medical Assessment and Research Centre (F-MARC).<sup>1</sup> Injury prevention starts with registration of injuries to find possible relations between risk factors, frequencies and characteristics of injuries. The F-MARC developed an injury monitoring assessment system that records the frequency and severity of injuries for each location.<sup>2,3,4</sup>

The F-MARC definition of a football injury is “any physical complaint caused by football”.<sup>5</sup> The severity of an injury is related to the number of days a soccer player is absent from regular trainings and/or matches. In general skin injuries due to a sliding do not lead to absence during a football training or match. These injuries are therefore qualified as a slight (0 days lost) injury.<sup>6</sup> Although skin injuries are not often severe in their appearance they are more common on artificial turf than on natural grass.<sup>7</sup>

A study performed by Zanetti et al. showed that artificial turf was generally judged to be better than the natural grass surface with the exception of the risk of abrasion caused by a sliding.<sup>8</sup> It was stated that skin abrasion is one of the most critical aspects for artificial pitches. According to Ekstrand et al. there might be an underestimation of skin injuries because of their low severity.<sup>9</sup> A method to classify the severity of skin injuries would improve the injury registration. Such a method helps to obtain more detailed information about skin related injuries. Currently, there is no method available to classify sliding induced skin injuries which is also related to the perceived sliding friendliness or perceived skin irritation. By definition the sliding friendliness perception is related to the sport surface and the perceived skin irritation is related to the sensory response of the player caused by a sliding.

The FIFA test 08 or ASTM F1015 test are now applied to evaluate the abrasiveness of soccer pitches.<sup>10,11</sup> Both methods are using skin replacers silicon and foam blocks, respectively. A limitation of both methods is that they do not simulate realistic vertical forces and velocity of a sliding. Another silicone based method to evaluate a sliding was developed by Sanchis et al. They developed a device to test the friction at realistic sliding conditions. This study showed a good correlation between the increased surface roughness of the tested silicone and players perception.<sup>12</sup> The use of skin replacers like silicone or foam blocks provide information about the abrasiveness of the sport surfaces but do not simulate the response of *in vivo* human skin and its biology when exposed to a sliding.

Peppelman et al. conducted a study to evaluate the skin after a sliding on different kinds of soccer pitches at clinical and histological level.<sup>13</sup> They showed the importance of

the skin biology to study skin damage caused by a sliding. Currently, an invasive method is relevant to study skin damage at histological level. Due to the invasiveness of such models, they are not ideal in studying skin damage. Therefore, the purpose of this study was to develop and validate a Skin Damage Area and Severity Index (SDASI) as a non-invasive readout system of the skin based on the clinical appearance of sliding damaged skin.

## Methods

The proposed method to score the skin damage caused by a sliding, called Skin Damage Area and Severity Index (SDASI), is based on the commonly used Psoriasis Area and Severity Index (PASI). The PASI is a dermatological tool to measure the severity of Psoriasis.<sup>14,15</sup> The SDASI is defined as the sum of the individual damage characteristics upon abrasion, erythema and type of exudation multiplied by the involved area score.

For development of this method, clinical pictures of sliding damaged skin were obtained from 14 male amateur soccer players in the age between 18 and 25 years. These Images were obtained from a previous study for which we got approval of the Ethics Committee.<sup>13</sup> The collected images were rated by an experienced dermatologist on the degree of abrasion, erythema and type of exudation. The rating resulted in a visual scale (Figure 1) of the different clinical parameters. This visual scale is used as a reference to evaluate skin injuries.

The extent of the relatively involved area of the skin lesion ( $A_{s,r}$ ) is complementing the SDASI and is defined as:

$$A_s/60 \text{ cm}^2 \times 100 \% \quad (1)$$

The involved area ( $A_s$ ) is measured with a transparent sheet containing a grid, the size of the grid was  $1 \times 1 \text{ cm}^2$ .

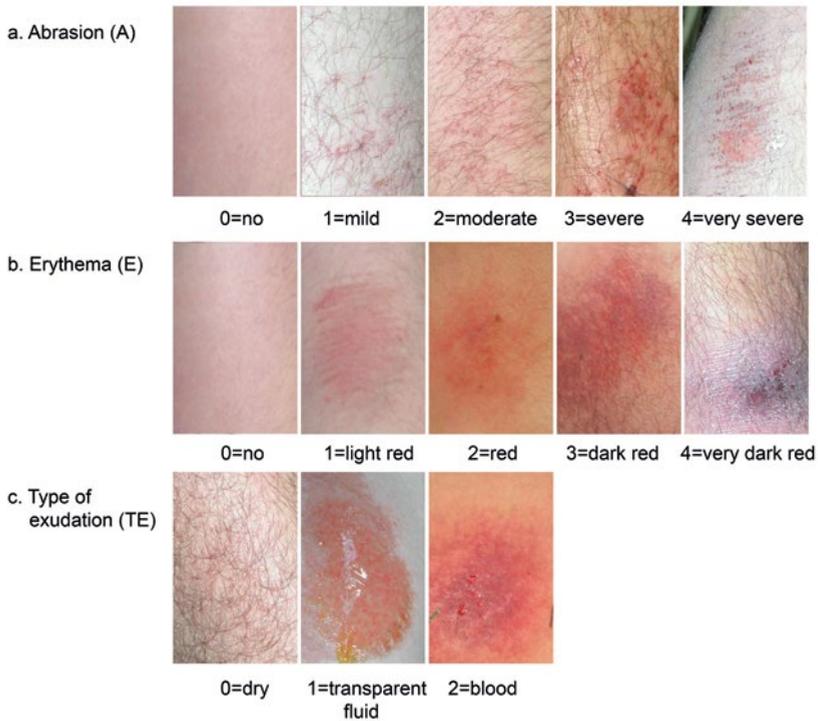
The following numerical value is given to the relative involved area :

0=no involvement; 1=  $\leq 10\%$ , 2=  $\geq 10\%$  but  $< 30\%$ , 3=  $\geq 30\%$  but  $< 50\%$ ,  
4=  $\geq 50\%$  but  $< 70\%$ , 5=  $\geq 70\%$  but  $< 90\%$  and 6=  $\geq 90\%$ .

Finally the SDASI can be calculated with the following formula:

$$\text{SDASI} = A_{s,r} \times (A + E + TE) \quad (2)$$

The range of the SDASI lies between 0 and 60.



**Figure 1** Visual scaling of the clinical parameters used in the SDASI. Abrasion **(a)** from 0 (no abrasion) to 4 (very severe abrasion) and erythema **(b)** from 0 (no erythema) to 4 (very severe erythema). The type of exudation **(c)** is classified as no exudation (0), exudation of a transparent fluid (1) or exudation of blood (2).

To test the practical feasibility of the developed SDASI, a randomized user trial was designed in which three different grades of infill materials were tested for their sliding friendliness by nine amateur soccer players.

The three infill materials included: an improved Thermoplastic Polyethylene (TPE-2), a commercial Thermoplastic Polyethylene (TPE) and a commercial Styrene-Butadiene-Rubber (SBR). These three types of infill were compared with a third-generation artificial turf configuration. The pitch was divided into three tracks of 4x20 m<sup>2</sup> each and prepared with the specific type of infill material.

Nine experienced amateur players with an age between 17-29 years and a skin type III or IV were included in the users trial. The average weight of the players was 72 kg ± 5 kg. Soccer players with skin diseases or a sensitive skin were excluded from this study. Each player performed two slidings per leg side per track towards a ball. In this way two

tracks were tested by one soccer player. By equal distribution of the leg sides over the three grades of infill the test protocol compensated for possible preferred leg side effects for a sliding. The user trial was conducted outdoor by  $22\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$  under dry conditions.

Directly after the sliding the SDASI was determined. The players sliding perception was obtained by a questionnaire. Two rating scales were presented concerning perceived skin irritation and perceived sliding friendliness. Respondents were asked to score the perceived skin irritation on an 11-point scale where 0=severe irritation and 10=no irritation.<sup>16</sup> The perceived sliding friendliness was scored on an 11-point scale where 0=very poor and 10=excellent.

All statistical analyses were performed with SPSS 18.0 for Windows.

The Pearson correlation coefficient was used to study the correlation between the clinical scores, perceived skin irritation and sliding friendliness

To study the possible difference in sliding performance the SDASI-score and reported rating for sliding friendliness and skin irritation of the three infill grades were analyzed with the one-tailed analyses of variance (ANOVA).

## Results

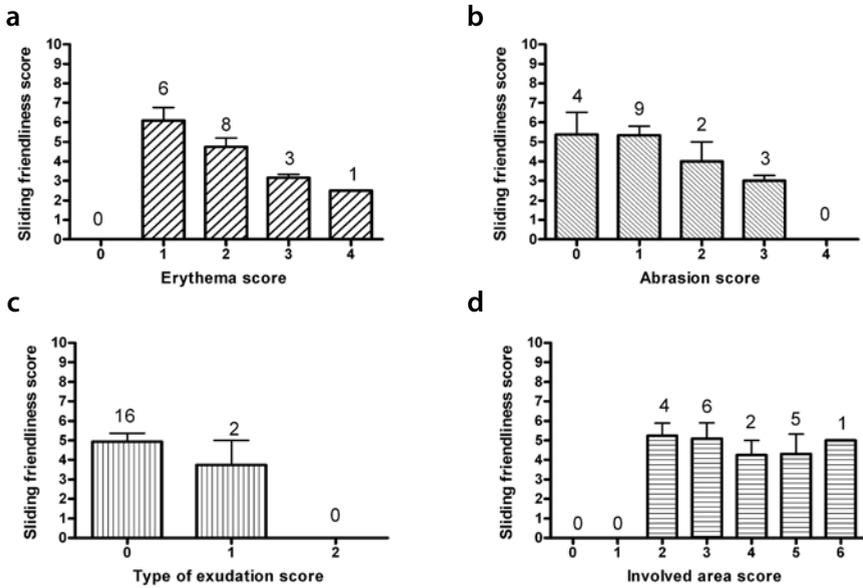
A correlation-analysis of the clinical scores, the perceived skin irritation and the sliding friendliness scores was performed with 18 unpaired observations from nine players.

Figure 2 shows that the erythema (fig 2a;  $r = -0.68, p < 0.01$ ) and abrasion (fig 2b;  $r = -0.51, p = 0.03$ ) correlated highly with the sliding friendliness. Table 1 clearly shows that the erythema ( $r = -0.69, p < 0.01$ ) and abrasion ( $r = -0.62, p < 0.01$ ) scores also correlated highly with the perceived skin irritation.

The clinical scores related to the size of the damaged skin area and the type of exudation however do not correlate with the perceived sliding friendliness and skin irritation. In addition, it was found that there was a strong correlation ( $r = 0.84, p < 0.01$ ) between the perceived skin irritation and the perceived sliding friendliness.

Most important, this correlation analysis showed a high reciprocal correlation between the proposed SDASI-score and both the perceived sliding friendliness ( $r = -0.58, p = 0.01$ ) and skin irritation ( $r = -0.53, p = 0.02$ ).

The analysis of variance results showed no significant differences between TPE-2, TPE and SBR infill grades with respect to the tested variables of the SDASI, sliding friendliness and skin irritation.



**Figure 2** Correlations of the clinical scores and the perceived sliding friendliness of 18 unpaired observations. The erythema score (a), abrasion score (b), type of exudation score (c) and involved area score (d) versus perceived sliding friendliness scores. The number of slidings are indicated above the error bars.

**Table 1** Correlation coefficients of Erythema score (1), Type of exudation score (2), Abrasion score (3), Involved area score (4), SDASI (5), perceived sliding friendliness (6) and perceived skin irritation (7) of all slidings (n=18).

1	p	2	p	3	p	4	p	5	p	6	p	
1	1											
2	0.44	0.068	1									
3	0.82**	0.000	0.28	0.257	1							
4	0.39	0.102	0.53*	0.023	0.48*	0.044	1					
5	0.87**	0.000	0.63**	0.005	0.86**	0.000	0.74**	0.000	1			
6	-0.68**	0.002	-0.23	0.367	-0.51*	0.031	-0.19	0.432	-0.58*	0.012	1	
7	-0.69**	0.002	-0.04	0.875	-0.62**	0.006	-0.055	0.828	-0.53*	0.024	0.84**	0.000

\* Correlation is significant at the 0.05 level (2-tailed)

\*\* Correlation is significant at the 0.01 level (2-tailed).

## Discussion

Although sliding induced skin lesions are by definition considered as a mild injury they are uncomfortable and it is reported that they are more common on artificial turf than on natural grass.<sup>7,8,9</sup> In the field of injury prevention, there is a need for safety and performance standards with respect to sliding friendliness. Due to the absence of an appropriate method to classify skin lesions only the frequency of skin injuries are sometimes reported. Therefore, the purpose of this study was to develop an evaluation method by using the skin itself as a non-invasive readout system. In line with the determination of the severity of the skin disease psoriasis by the PASI-score, we developed the Skin Damage Area and Severity Index (SDASI).

The results of the controlled user trial showed that the SDASI score correlates very well with the perceived skin irritation and sliding friendliness of a soccer player. Further, the correlation-analysis of the clinical scores suggests that not all scores are correlating with the perceived skin discomfort. The degree of skin abrasion and erythema are directly linked to discomfort. Especially the correlation between the degree of erythema and the perceived sliding friendliness proved to be very strong.

In order to get a more sensitive readout in future studies, it could be interestingly to use proven instrumental techniques like colorimetry or reflectometry to measure the erythema.<sup>17,18,19</sup> The advantage of the proposed SDASI as a psychosensorial assessment is that it can be used anywhere, is non-invasive and therefore can be used to test a large number of subjects. Only a small effort in training of the observers is necessary to get reliable results.

The perceived discomfort seems to be independent of the type of exudation and involved area. These are typically wound parameters that provide information about the volume of a skin injury. The scores of the type of exudation suggest that a sliding performed upon a third-generation artificial turf pitch does not cause deep wounds. Only 2 out of 18 evaluated slidings showed signs of exudation. When the results of the involved area scores are combined with the erythema scores it can be seen that a sliding always results in at least slight erythema with a minimum involved area of 6 cm<sup>2</sup>.

Although the type of exudation and involved area suggests not to be relevant for the perceived discomfort these parameters could be of interest in the monitoring and prediction of the healing of the injured skin.<sup>20</sup> The current study did not focus on the recovery process of the skin injury where possible inflammation and scarring are main topics. Neither secondary effects such as infection were evaluated. New non-invasive techniques with the use of reflectance confocal *in vivo* microscopy can provide valuable information of the deeper epidermal and subepidermal effects of a sliding and its recovery process.<sup>21</sup>

The current study contained a feasibility trial to compare three grades of infill for their sliding friendliness by using both the objective SDASI-score and the subjective perceived

sliding friendliness. The three types of infill (TPE-2, TPE and SBR) did not significantly differ from each other with regard to the SDASI-score, perceived sliding friendliness and skin irritation. However, Zanetti et al. found significant differences in the performance of SBR and TPE filled soccer pitches where players prefer SBR compared to TPE with regard to skin abrasion.<sup>8</sup>

## Conclusion

This study demonstrated that the newly developed scoring system is not only able to quantify a sliding induced skin lesion but also correlates very well with perceived discomfort.

The future step would be to integrate the SDASI in the injury monitoring system and start collecting data to obtain insight in the severity of sliding skin lesions due to a sliding of current artificial pitches worldwide.

## Practical implications

- The development of the SDASI makes it possible to quantify the severity of skin injuries caused by a sliding.
- Compared to instrumental techniques for quantification of skin injuries, the SDASI is cheap and can be used anywhere and therefore can be used to test large numbers of subjects.
- The developed skin injury index correlates very well with the perceived sliding friendliness and perceived skin comfort.

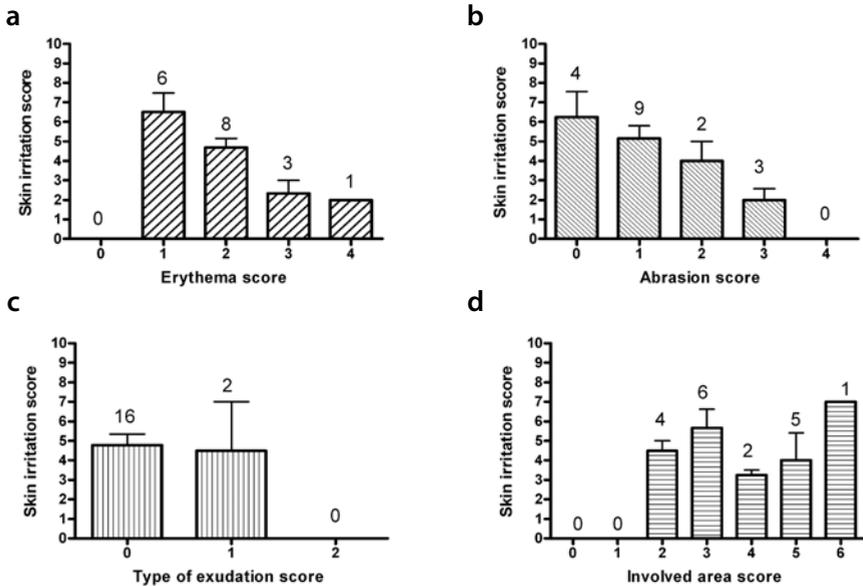
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## Supplementary data

**Table** Analysis of variance results of sliding performance tests performed upon artificial turf with three different types of infill materials (TPE-2, TPE en SBR) regarding SDASI, perceived sliding friendliness and skin irritation scores.

	TPE-2 (n=6)	TPE (n=6)	SBR (n=6)	F	p
	Mean (SD)	Mean (SD)	Mean (SD)		
SDASI [0-60]	21.2 (12.3)	7.3 (3.5)	11.0 (10.6)	3.36	0.062
Sliding friendliness [0-10]	3.9 (1.2)	5.8 (1.8)	4.8 (2.2)	1.95	0.177
Skin irritation [0-10]	3.8 (2.2)	5.9 (2.2)	4.5 (2.3)	1.37	0.285



**Figure** Correlations of the clinical scores and the perceived skin irritation of 18 unpaired observations. The erythema score (a), abrasion score (b), type of exudation score (c) and involved area score (d) versus perceived sliding friendliness scores. The number of slidings are indicated above the error bars.



# 3

## Understanding the skin injury mechanism



# 3.1

## Combining tape stripping and non-invasive reflectance confocal microscopy: an in vivo model to study skin damage

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## Abstract

**Background:** Evaluation of (immuno)histological and cell biological changes in damaged skin requires often an invasive skin biopsy, making in vivo models inappropriate to study skin damage. Reflectance confocal microscopy (RCM) might overcome this limitation. Therefore, we evaluated the use of a tape-stripping model in combination with RCM to provide morphological data on skin damage and recovery.

**Methods:** In 25 volunteers, a tape-stripping stimulus was applied. The skin was imaged with RCM during 1 week and 3 mm punch biopsies were obtained.

**Results:** Strong correlations between epidermal thickness determined by RCM and conventional histological measurements were found. RCM thickness measurements correlated well with epidermal proliferation. The 10x or 15x repeated tape-stripping resulted in skin damage similar to acute stripping. Mild repeated tape-stripping showed no skin damage.

**Conclusion:** Overall, we demonstrated that non-invasive RCM in combination with tape-stripping could be used as model to obtain morphological and cell biological data on skin-material interactions.

## Introduction

Skin serves as the interface between humans and their environment, thereby protecting the body against negative environmental influences. This is achieved by its multi-layered structure. The barrier function is mainly regulated by the outermost layer of the skin, called the stratum corneum (SC). This layer is produced by the process of cornification, resulting in layers of tightly packed flattened anucleated skin cells mainly full of keratin. These cells are embedded in a lipidic intercellular matrix composed of ceramides, long-chain free fatty acids and cholesterol.<sup>1,2</sup> In addition to the SC, the antimicrobial and innate immunity barrier is regulated by the living epidermal layer below the SC.<sup>2</sup>

Disruption of the skin barrier function is often studied at a biological level in skin diseases e.g. in wounds.<sup>3,4</sup> However, studies on mechanical skin damage are rare. Mechanical skin injury can be caused by performing sports, in case the skin interacts with the playground.<sup>5,6</sup> or in a car accident where airbags protect against life threatening injuries but meanwhile cause abrasion type of skin injuries.<sup>7,8</sup> The cell biological effects on the skin after skin-material interaction; however, may be of importance when developing skin friendlier materials and products. With (immuno)histopathology, these cell biological changes in the skin can be studied.<sup>5</sup> At present, for this purpose, an invasive skin biopsy is still required, which is troublesome while studying skin damage as result of skin-material interaction, as the extra inflammation caused by the biopsy will interfere with the results of the experiment.

Currently available methods to investigate skin-material interactions do not use the skin as readout system. These models only study the interaction between two different kinds of materials, one of which represents the skin.<sup>9,10</sup> It is difficult to translate results obtained by these methods to human skin, as clinical appearance and skin histology cannot be evaluated over time. An *in vivo* skin damage model combined with a non-invasive readout technique could build a bridge between the clinic, fundamental science and industry, contributing to the development of user-friendlier materials and products.

The *in vivo* sellotape-stripping model, which is commonly used for studying the skin barrier function, epidermal growth, and concurrent immune responses, might be useful to study skin damage related to skin-material interaction.<sup>11,12,13,14</sup> This model is a minimal invasive procedure for the removal and sampling of the SC. *In vivo* biotribology measurements have been performed in this model; however, a skin biopsy is still required to evaluate the histological and cell biological changes in the skin.<sup>15</sup> While studying skin damage, this is troublesome as mentioned above, as the extra inflammation caused by the biopsy will interfere with the experiment results. Non-invasive imaging tools such as high-frequency ultrasound and optical coherent tomography have resolutions that only reveal architectural changes of the skin.<sup>16</sup> These techniques do not allow identification of cellular or sub-cellular structures and therefore will not yield the missing information in the field of mechanical skin damage. Reflectance confocal microscopy (RCM) on the other

hand is a non-invasive imaging technique, which is used for in vivo evaluation of skin morphology, which offers a resolution and contrast comparable to conventional light microscopy.<sup>17,18</sup> This technique allows to image cells to a depth of about 250  $\mu\text{m}$  below the SC. In confocal images, contrast is provided by refractive index differences between cells and surrounding tissue. The contrast of in vivo RCM imaging of the skin is mainly provided by melanin and keratin. In contrast to these highly reflective structures, white blood cells, chromatin, collagen, and elastin show lower reflection.<sup>17,18,19</sup> This imaging technique is currently used for diagnosis of skin cancer and inflammatory skin diseases.<sup>20,21,22,23,24,25,26</sup> Further, it is shown that RCM can be used for follow-up of therapy and studying dynamic inflammatory processes in vivo.<sup>27,28,29</sup>

The aim of this study is to evaluate the tape-stripping model in combination with non-invasive in vivo RCM in order to study mechanical skin damage and recovery over time. In the standard tape-stripping model the whole SC is stripped off, thereby significantly disturbing the skin barrier function. However, after skin-material interaction, total removal of the corneal layer is not always the case.<sup>5</sup> Gerritsen et al. studied single vs. constituted tape-stripping, to evaluate the immune response.<sup>11</sup> Consistent with this, we questioned whether the tape-stripping model can be used as an acute (e.g. sliding on a playing ground or airbag impact) as well as a chronic (e.g. daily shaving or repeated skin scrubbing) mechanical skin damage model. Combining the tape-stripping model with RCM imaging may prevent the necessity to perform skin biopsies in healthy volunteers and may provide a non-invasive skin damage model in which the skin is used as a readout system. In this model it is possible to monitor skin changes over time. Therefore, this non-invasive model may increase our knowledge on mechanical disruption and recovery of the skin at a (cell) biological level over time, thereby contributing to the development of more skin friendlier material and products.

## Materials and Methods

### Healthy volunteers

In this study, 25 healthy adults, 9 males and 16 females, with a mean age of 24 years (SD 4.9), and skin type I, II, or III were included after giving written informed consent. Volunteers with a history or signs of chronic skin diseases, disturbed wound healing, an activated immune system, or immunocompromised volunteers were excluded from participation. Two weeks prior to the experiments, volunteers were not allowed to expose their lower back skin to sunlight. This study was conducted according to the principles of the Declaration of Helsinki and was approved by the local medical ethics committee. Measurements were performed at the department of Dermatology, Radboud University.

### Tape-stripping procedure

The volunteers were randomized over two groups, one received an acute tape-stripping stimulus and the other group received a repeated tape-stripping stimulus. In all volunteers, tape stripping was performed on several sites (2 x 1 cm<sup>2</sup>) on the lower back skin. For the acute skin damage stimulus (n = 12), the adhesive tape (Sellotape Original 1109; Borehamwood, UK) was sequentially applied and removed (25–30x) onto the skin surface until the skin glistened. In this way, all layers of the SC were removed and provided a standardized trauma of the skin.<sup>12,30,31</sup> For the repeated skin damage stimulus (n = 13), three different frequencies of tape stripping were used for 5 consecutive days. The frequencies included 5x (n = 4), 10x (n = 4) or 15x (n = 5) tape stripping, respectively. All time intervals were based on a pilot study performed at our department and a literature search.<sup>11,32,33</sup>

### RCM imaging

Reflectance confocal microscopy imaging was performed with the commercially available VivaScope 1500 system (Lucid Inc. Rochester, NY, USA). Images were obtained and analyzed using Vivascan 7.0 software (Lucid Inc.). A more extensive description of the RCM technology has been published previously.<sup>17,18,19</sup> RCM images and clinical pictures with the Vivacam (Lucid Inc.) were obtained before and instantly after the first tape-stripping moment. These measurements were repeated at 24 h, 72 h, and 1 week after the first measurements. At 48 h and 96 h, in combination with the tape stripping, additional measurements were performed in the repeated tape-stripping group. The RCM images were obtained according to a standardized protocol. A horizontal map of 4 x 4 mm<sup>2</sup> (Vivablock) was made at the level of the SC, stratum spinosum, dermal–epidermal junction and papillary dermis. Within the area of interest, two vertical mappings (Vivastack) were performed. This mapping included a series of images of 0.5 x 0.5 mm in depth with steps of 4.5 μm, started at the top of the SC until the papillary dermis. Moving features were captured by short videos.

### Histology and immunohistochemistry

To correlate the RCM images, 3 mm skin biopsies were taken under local anesthesia with 1% Xylocain/Adrenalin. A biopsy of healthy skin was obtained as reference and internal control. Taking the ethical aspects into account, a biopsy was not obtained at 48 h in order to minimize the number of biopsies. The biopsies were embedded in paraffin after 4 h fixation in formalin. Paraffin sections (6 μm) were deparaffinized with histosafe (Adamas, Rhenen, The Netherlands) followed by rehydration in decreasing concentrations of alcohol (100–50%). The sections were hematoxylin-eosin (HE) stained for assessment of histopathological features. In addition, immunohistochemical (IHC) staining was performed with monoclonal anti-human primary antibodies specific for CD3 (1:500, clone F7.2.38; Abcam, Cambridge, UK), elastase (1:50,000, clone NP57; DAKO, Copenhagen, Denmark), CD31(1:100, clone JC70A; DAKO), cytokeratin 16 (K16) (1:500, clone LL025; Monosan, Uden,

The Netherlands), and Ki67 (1:100, clone MIB-1; DAKO). CD3 and elastase staining was performed to stain T-lymphocytes and polymorphonuclear leukocytes (PMN), respectively. CD31 stains the endothelial cells of the blood vessels. Cytokeratin 16 and Ki67 were performed in order to evaluate keratinocyte differentiation and proliferation. The sections for the CD3, elastase, CD31, and Ki67 staining were pretreated with 3 % H<sub>2</sub>O<sub>2</sub> in methanol for 15 min, in order to omit endogenous peroxidase activity. For the CD3 immunostaining, the sections were antigen retrieved by boiling the sections in EDTA (pH 8.0, 0.5 % Tween) for 10 min. For the CD31, K16, and Ki67 staining, antigen retrieval was achieved by boiling the sections in citrate (pH 6.0) for 10 min. Antigen retrieval was not needed for the elastase staining. For all sections, this initial step was followed by incubation for 15 min with 1% bovine serum albumin (Sigma-Aldrich, St. Louis, MO, USA) in PBS, in order to block non-specific binding. Next, overnight incubation with the primary antibody was performed. This step was followed by incubation with HRP antimouse Envision (DAKO) for 30 min. To detect the primary antibody, the sections were washed in PBS and the HRP was visualized using 3,3' diaminobenzidine. Sections were counter-stained with Mayer's hematoxylin (Sigma-Aldrich) and after dehydration the slides were mounted in Permount (BDH Chemicals, Poole, England). Finally, the sections were photographed using a microscope (Axioskop2 MOT; Zeiss, Jena, Germany), digital camera (AxioCam MRc5; Zeiss) and AxioVision software (Zeiss).

### Thickness measurements

The HE stained tissue sections were used to measure the SC at five points of which the average was considered as the SC thickness (AxioVisio software, Zeiss). For the RCM images, two Vivastacks were evaluated. The SC thickness was determined by counting the steps (4.5 µm) in depth, starting at the outermost layer of the skin till the stratum granulosum, in which the first nucleated cells appear. The thickness of the living epidermis was determined for the RCM as well as the histological images. For the RCM images, this thickness was determined by counting the steps (4.5 µm) in depth, starting at the stratum granulosum till the first dermal papillae appeared. The epidermal thickness present in the histological sections was determined by the average of the five thinnest points of the epidermis, corresponding to the tips of the dermal papillae.

### Inflammation and epidermal proliferation

CD3 positive cells or elastase positive cells were scored in the IHC stained sections. The scoring was defined as normal (N), mild increased influx of inflammatory cells (±), severe increased influx of inflammatory cells (+). In addition, all RCM images were evaluated for the presence or absence of highly reflective inflammatory cells in the epidermis and dermis. In the Ki67 stained tissue sections, the number of Ki67 positive nuclei per mm epidermis were counted using AxioVision software 4.8 (Zeiss). In addition, cytokeratin 16 expression was scored as absent (-), mild expression (±) or strong expression (+). All HE

stained sections and all RCM images were scored for the presence or absence of parakeratosis and spongiosis. Further, loss of the honeycomb pattern in the epidermis was evaluated.

### Vascularisation, ratio basal membrane-stratum corneum, and number of papillae

In the dermis, the area positive for CD31 IHC staining was measured using ImageJ software 1.46. Further the ratio between the length of the basal membrane and length of the SC was determined. With RCM the number of dermal papillae per  $\text{mm}^2$  was counted at the level of the dermal–epidermal junction.

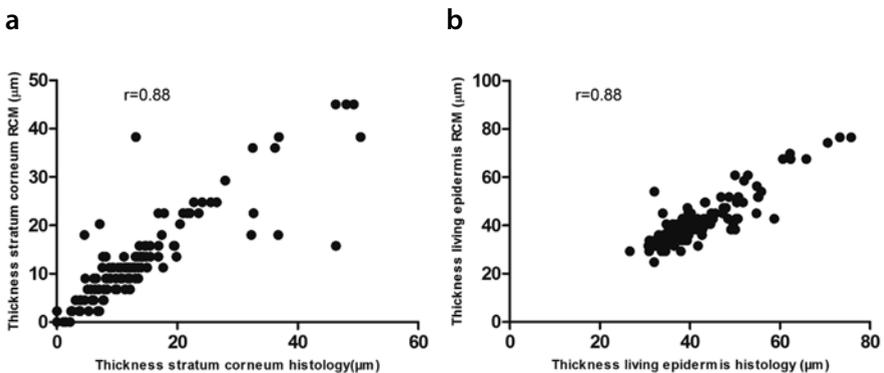
### Statistical analysis

Correlations between RCM, histology and IHC measurements were calculated by a Pearson correlation analysis, using GraphPad Prism software 5.03. ANOVA analysis with post-hoc testing was used to compare values of the different groups and time points. Throughout the analysis,  $p < 0.05$  were considered significant.

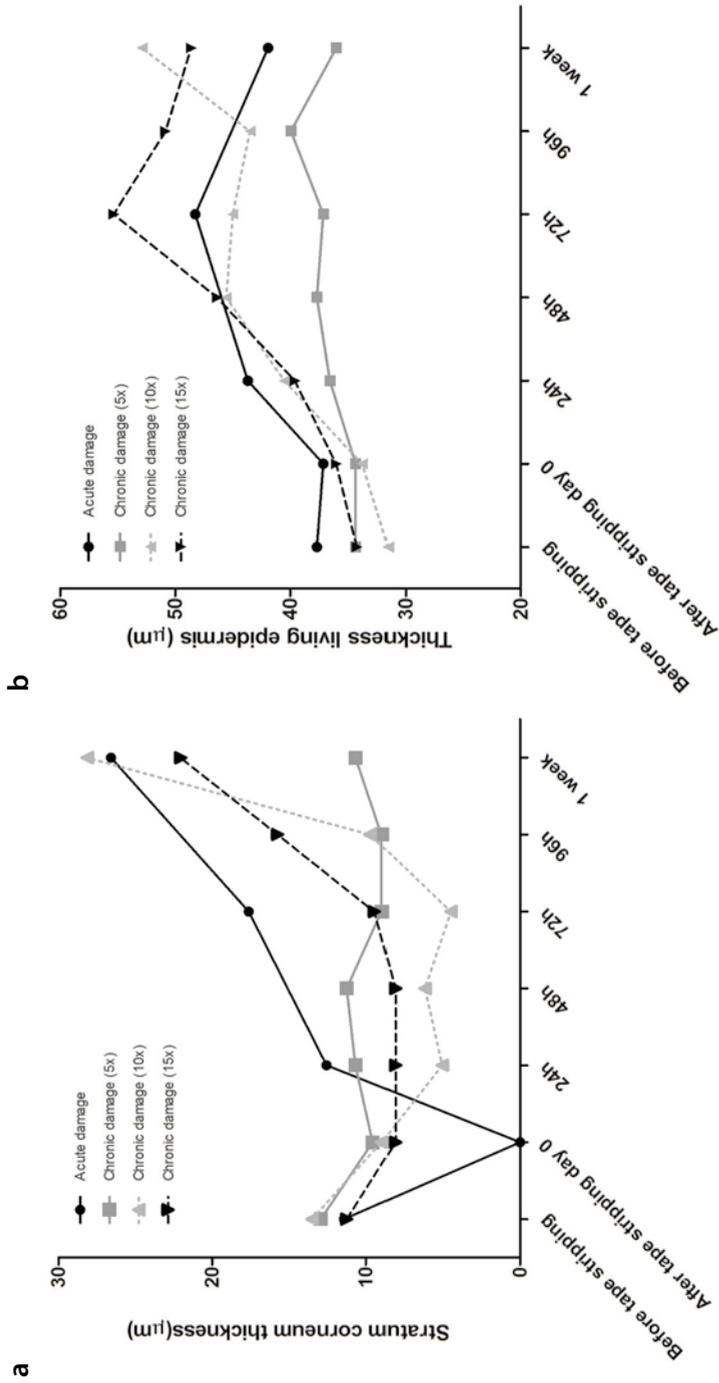
## Results

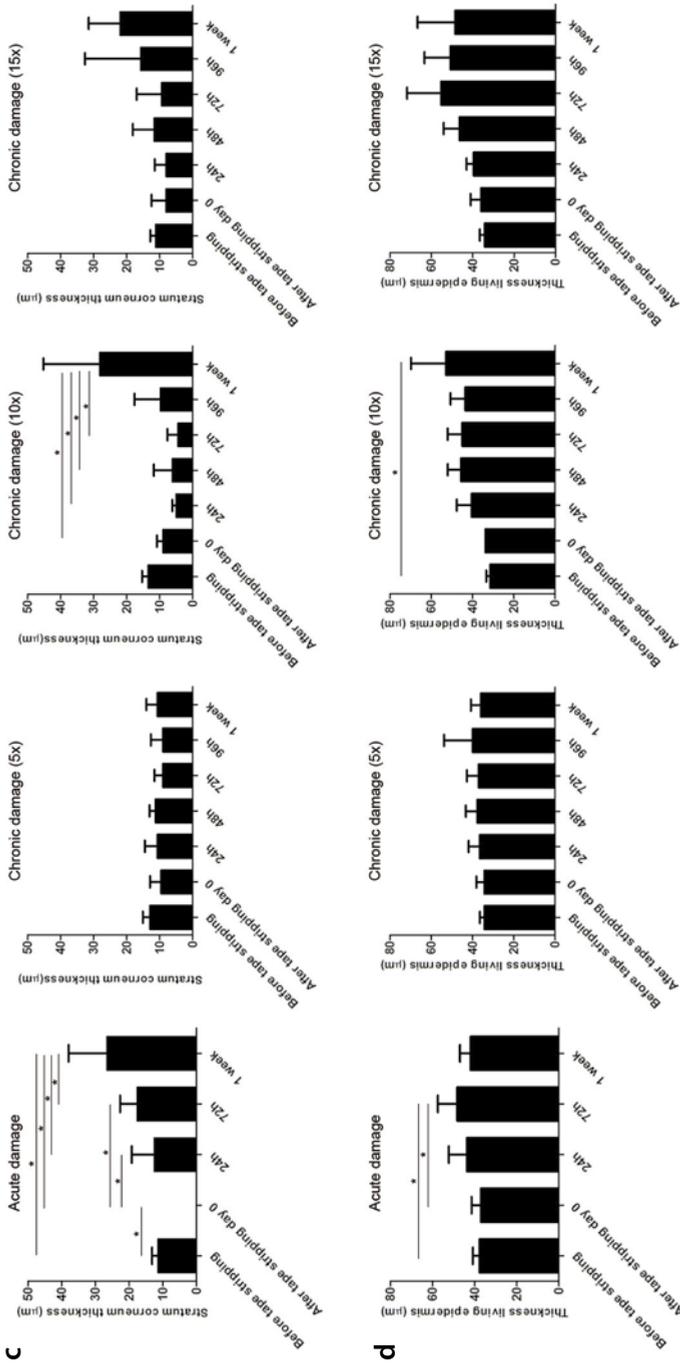
### Correlation between RCM and histology thickness measurements

A strong correlation (Pearson  $r = 0.88$ ) was found between histology and RCM images for both the SC and living epidermal thickness measurements (Figure 1). As expected, instantly after the tape-stripping stimulus, significant differences in SC thickness were found between the acute and repeated (5x) tape-stripping model. At this time point, in



**Figure 1** Correlation between thickness measurements based on histological sections and RCM imaging. (a) Stratum corneum thickness measurements. (b) Thickness of the living epidermis.

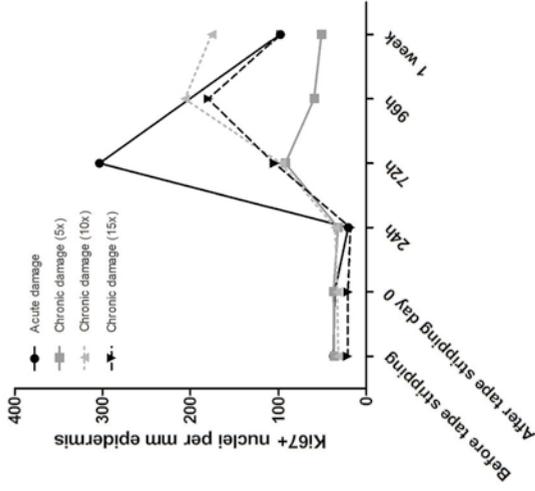




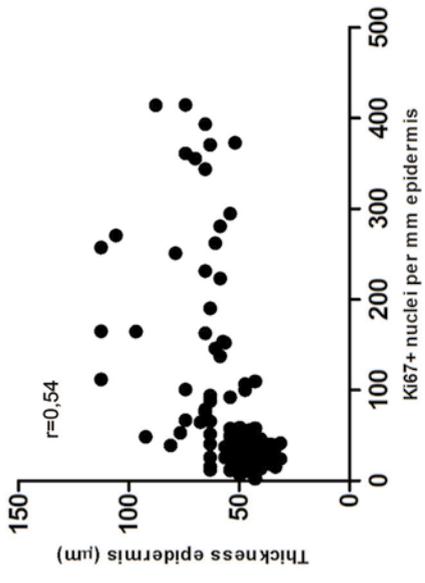
**Figure 2** RCM thickness measurements. **(a)** Summary of stratum corneum thickness measurements over time for all tape-stripping stimuli. **(b)** Overview of the average thickness of the living epidermis for each skin damage group over time. **(c)** Graphs of the average stratum corneum thickness for each tape-stripping stimuli, including standard deviations. **(d)** The average thickness with standard deviation of the living epidermis thickness measurements for each tape-stripping stimuli. Significant differences between measurements are indicated by an asterisk (\*).

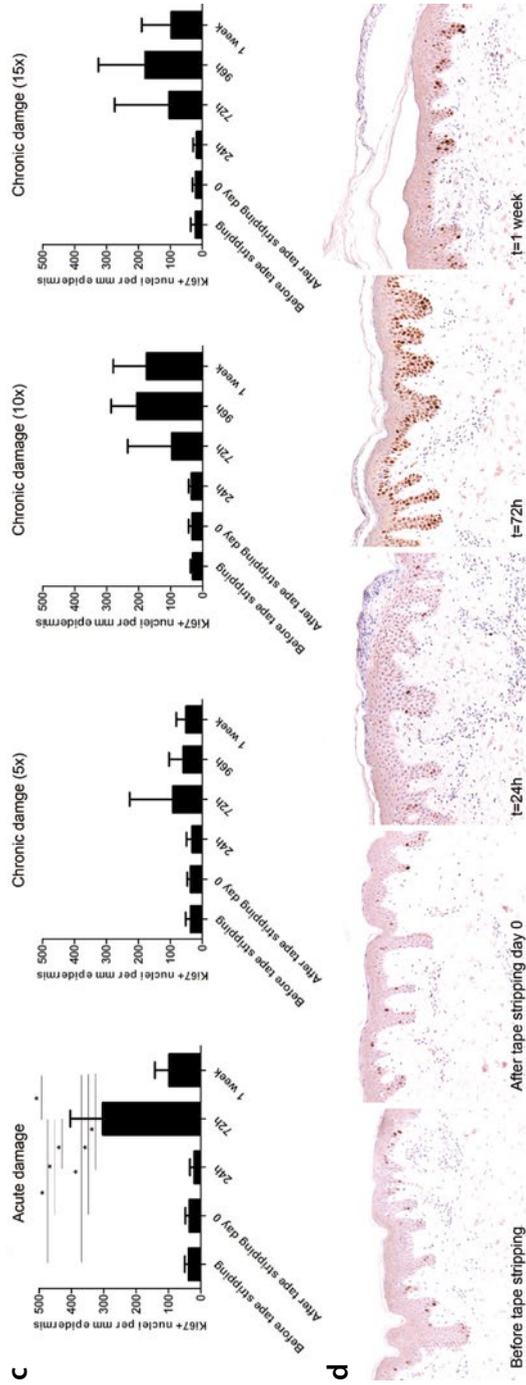


a



b





**Figure 3** Epidermal proliferation as result of acute and repeated skin damage. **(a)** Overview of Ki67 expression in all tape-stripping groups over time. **(b)** Correlation between epidermal thickness and the number of Ki67+ nuclei per mm epidermis. **(c)** Graphs of Ki67 expression, including standard deviation, in each tape-stripping group. Significant differences ( $p < 0.05$ ) are depicted with an asterisk (\*). **(d)** Representative photographs of Ki67 immunohistochemically stained tissue sections before and after acute skin damage.

the acute model, the SC was totally removed, whereas in the 5x repeated tape-stripping group a minimal decrease in thickness was observed (Figure 2a). Because of large standard deviations we did not observe significant differences between the other stimuli (Figure 2c). However, instantly after the first tape stripping, 10x and 15x tape stripping seem to result in less skin damage compared to the acute stimulus.

In contrast to acute tape stripping, independent of the tape-strip frequency, the total SC was never totally removed during and after repeated tape stripping (Figure 2a and c). Acute tape stripping resulted in a significant increase of SC thickness 72 h after tape stripping and increased even more a week after the stimulus was applied (Figure 2c). After the last tape-stripping moment in the 10x and 15x tape repeated-stripping groups, SC thickening was comparable to acute tape stripping. This SC thickening was never observed after 5x tape stripping for 5 consecutive days (Figures 2a and c). The thickness of the living epidermis significantly increased 72 h after acute tape stripping (Figures 2b and d). Although as late as 1 week after the tape stripping was started, this thickening was also observed in the 10x and 15x repeated tape-stripping groups. For the 5x repeated tape stripping, again no significant differences were found between measurements, the thickness of the living epidermis remained equal (Figures 2b and d).

### **RCM thickness measurements as a measure for keratinocyte proliferation in vivo**

In the basal layer, a significantly increased number of proliferating keratinocytes was present 72 h after acute tape stripping. Although the number of Ki67 positive cells decreased 96 h and 1 week after tape stripping, it remained significantly increased compared to the number of Ki67 positive keratinocytes before, instantly after and 24 h after tape stripping (Figures 3a, c and d). The 10x and 15x repeated tape-stripping stimulus followed this line with a small delay in time, showing a peak in proliferating keratinocytes 96 h after the first tape-stripping stimulus. The number of Ki67 positive cells in these groups was lower compared to acute tape stripping. One week after the first stimulus, the number of proliferating cells decreased as well in these two repeated tape-stripping groups. Consistent with the thickness measurements, 5x repeated tape stripping showed a constant number of Ki67 positive cells, with no significant differences between time points (Figure 3c). A Pearson analysis resulted in a moderate to strong correlation ( $r = 0.54$ ) between the number of Ki67 positive keratinocytes and the epidermal thickness (SC + living epidermis; Figure 3b). For all stimuli, cytokeratin 16 expression showed a trend comparable to the Ki67 expression (Table 1, Supplementary Figure).

### **Parakeratosis, epidermal atypia and spongiosis**

As a result of hyperproliferation and wound recovery, parakeratosis was observed 24 h, 72 h and 1 week after acute skin damage. 10x and 15x tape stripping for 5 consecutive days resulted mainly in parakeratosis 72 h or later after the first tape-stripping moment. The 5x

**Table 1** Overview of the scoring of cytokeratin 16, CD3 and elastase immunohistochemical staining in all tape stripping stimuli over time. Cytokeratin 16 expression in the epidermis was scored as absent (-), mild expression ( $\pm$ ), strong expression (+). CD3 and elastase positive cells were not present in the epidermis, therefore they were only scored in the dermis. The presence of these inflammatory cells was scored as normal (N), mild increased dermal infiltrate ( $\pm$ ), strong increased dermal infiltrate (+).

	Time	Cytokeratin 16			CD3			Elastase		
		-	$\pm$	+	N	$\pm$	+	N	$\pm$	+
<b>Acute damage (n=12)</b>	Before tape stripping	100%	0%	0%	100%	0%	0%	100%	0%	0%
	After tape stripping	100%	0%	0%	100%	0%	0%	100%	0%	0%
	24h	58%	25%	17%	41.5%	17%	17%	8%	17%	75%
	72h	17%	33%	50%	17%	25%	58%	25%	50%	25%
	1 week	25%	58%	17%	50%	33%	17%	92%	8%	0%
<b>Repeated damage (15x) (n=5)</b>	Before tape stripping	100%	0%	0%	100%	0%	0%	100%	0%	0%
	After tape stripping	100%	0%	0%	100%	0%	0%	100%	0%	0%
	24h	100%	0%	0%	80%	0%	20%	60%	0%	40%
	72h	40%	20%	20%	20%	20%	60%	40%	20%	40%
	96h	40%	20%	40%	20%	20%	60%	80%	0%	20%
1 week	60%	20%	20%	20%	20%	60%	80%	0%	20%	
<b>Repeated damage (10x) (n=4)</b>	Before tape stripping	100%	0%	0%	100%	0%	0%	100%	0%	0%
	After tape stripping	100%	0%	0%	100%	0%	0%	100%	0%	0%
	24h	100%	0%	0%	100%	0%	0%	75%	25%	0%
	72h	100%	0%	0%	25%	0%	75%	75%	0%	25%
	96h	75%	0%	25%	50%	0%	50%	75%	25%	0%
1 week	75%	0%	25%	25%	0%	75%	50%	50%	0%	
<b>Repeated damage (5x) (n=4)</b>	Before tape stripping	100%	0%	0%	100%	0%	0%	100%	0%	0%
	After tape stripping	100%	0%	0%	100%	0%	0%	100%	0%	0%
	24h	100%	0%	0%	100%	0%	0%	100%	0%	0%
	72h	75%	25%	0%	50%	0%	50%	75%	0%	25%
	96h	75%	25%	0%	25%	0%	75%	75%	25%	0%
1 week	100%	0%	0%	75%	0%	25%	50%	50%	0%	

repeated tape-stripping stimulus did not result in parakeratosis. Scoring of parakeratosis based on RCM and histology corresponded well (Figure 4). Although loss of the honey-comb pattern, indicating epidermal atypia, and spongiosis could be observed with RCM, no correlation was found between this measure and epidermal proliferation, thickness, or other parameters (Figures 4g and h).

### **Absence of epidermal inflammation**

Influx of highly reflective inflammatory cells into the epidermis was not observed by RCM imaging. This corresponded very well with the observations in the CD3 and elastase IHC stained tissue sections, since no inflammatory cells were found in the epidermis. IHC staining showed some influx of PMN and T-cells in the dermis (Table 1, Supplementary Figure). Unfortunately, limitations in penetration depth and epidermal thickening did not allow visualization of these cells with RCM.

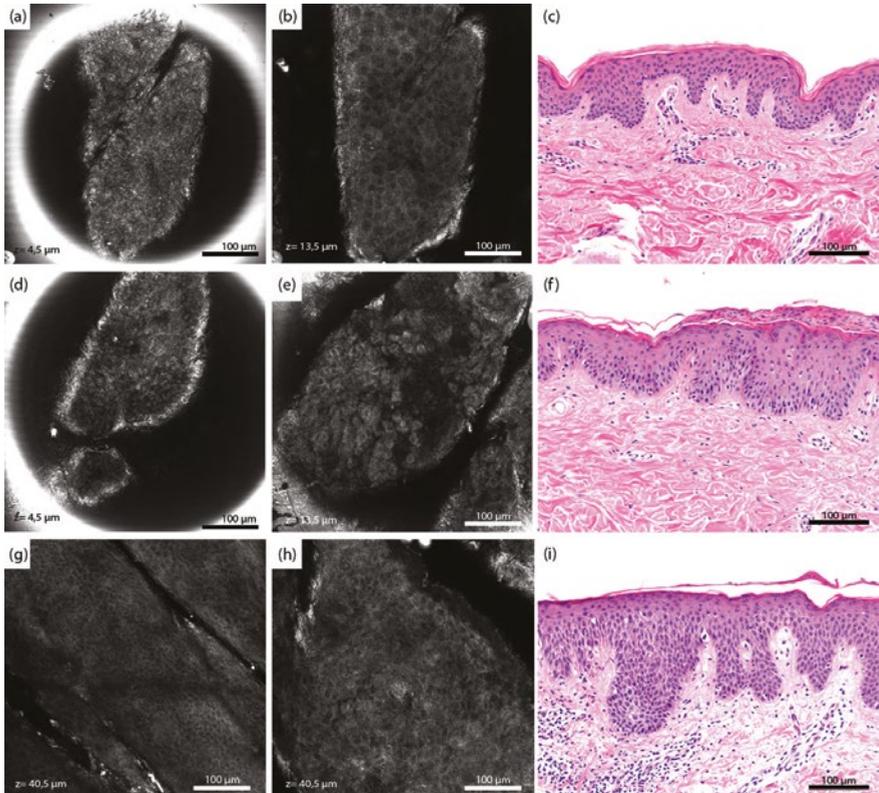
### **Vascularization in relation to the basal layer and papillae**

At 24 h after the acute tape-stripping challenge, the CD31 positive area in the dermis increased to some extent (Supplementary Figure). For the 10x and 15x repeated tape-stripping stimulus, this increase was observed after 72 h. Again, 5x repeated tape stripping did not result in differences over time. In order to define a RCM measure for vascularization, the number of papillae was counted. Unfortunately, this was only possible in a low number of volunteers, which did not allow to determine differences in the number of papillae between the groups and over time. This ensured that no reliable correlation analysis between the number of papillae and CD31+ area in the dermis or number of proliferating cells could be performed.

Acute, 10x repeated and 15x repeated tape stripping, resulted in a small increased ratio of basement membrane length over SC length (BM/SC ratio) over time. Although a trend could be observed, significant differences between all tape-stripping stimuli were not found. In addition, 5x tape stripping did not result in changes in the BM/SC ratio. The calculated ratio did not correlate to the number of proliferating cells (Pearson  $r = 0.13$ ) or area positive for CD31 staining (Pearson  $r = 0.05$ ).

## **Discussion**

We studied the value of the tape-stripping model combined with in vivo RCM imaging as a non-invasive method to investigate skin damage and recovery over time after mechanical skin-material interaction. The induced skin changes were followed with multiple techniques to validate non-invasive RCM imaging as a technique in this field. RCM images were correlated with conventional (immuno)histopathology in order to provide evidence for a non-invasive model for future use.



**Figure 4** RCM images in the horizontal plane and pictures of hematoxylin-eosin stained vertical sliced tissue sections of normal skin, parakeratosis, epidermal atypia, and mild spongiosis. **(a)** RCM image at the level of the stratum corneum at which no nucleated cells can be seen. **(b)** At the level of the stratum granulosum, the first nucleated cells appear as dark rounds with a brighter halo representing the nucleus with the surrounding cytoplasm. **(c)** Conventional hematoxylin-eosin stained tissue section of normal skin. Showing a thin stratum corneum, with no nucleated cells. The keratinocytes in the stratum spinosum are similar in appearance and are ordered in a regular pattern. **(d)** RCM image at the level of the stratum corneum, small highly reflective bright particles are visible representing parakeratosis. **(e)** Due to the thickening of the stratum corneum the stratum granulosum is not visible at the same level as in normal skin. This image shows the presence of bright nucleated cells within the stratum corneum, indicating parakeratosis. **(f)** Hematoxylin-eosin stained tissue section of parakeratotic skin. The stratum corneum is thickened and nucleated cells are present within this layer (right corner). **(g)** RCM image of normal skin at the level of the stratum spinosum, showing a regular honeycomb pattern. **(h)** 72 h after acute skin damage, epidermal atypia is visible represented by the loss of the honeycomb pattern and some bright intracellular spaces are visible representing mild spongiosis. **(i)** Hematoxylin-eosin stained tissue section showing epidermal atypia. Keratinocytes differ in size and shape and are surrounded by some spongiosis.

Thickness as measured in RCM images showed a strong correlation with the thickness as seen in histology for both SC and living epidermis. Thus, RCM can be used as a non-invasive tool to measure epidermal thickness *in vivo*. Thickness measurements of the acute skin damage model are consistent with previous reported data.<sup>30,31,32,33</sup> With a small delay in time, repeated tape stripping for 5 consecutive days with a frequency of 10x or 15x induced skin changes comparable to those observed after acute tape stripping. For this reason the acute tape-stripping model may perhaps be useful in studying both acute and repeated skin damage. In contrast to 10x and 15x repeated tape stripping, mild tape stripping (5x) for 5 consecutive days did not result in skin changes, indicating a threshold value for development of skin damage and recovery.

Interestingly, the *in vivo* epidermal thickness measurements with RCM correlated well to the number of Ki67-positive cells as seen in histology, thus representing a non-invasive *in vivo* measure for epidermal proliferation. The observed expression of the hyperproliferation markers Ki67 and cytokeratin 16 in the used models are consistent with previous described data on tape stripping.<sup>32,33,34</sup> Although a small reduction in keratinocyte proliferation was observed 24 h after acute tape stripping, we did not find significant differences between the time points. We therefore, were not able to confirm the hypothesis made by Hendriks et al. that the mechanical stressor transiently paralyzes the basal keratinocytes after 24 h.<sup>32</sup>

Besides epidermal proliferation and abnormal differentiation, parakeratosis (a measure for wound healing) can also be very well visualized with RCM. Keratinocyte atypia may be present in case of disturbed proliferation. Other processes like stress, environmental factors, or skin diseases can also induce keratinocyte atypia and concurrent spongiosis, explaining the variety in the presence of epidermal atypia in the evaluated skin damage model. However, when present, RCM imaging allows visualization of epidermal atypia and spongiosis.

Measurement of transepidermal water loss (TEWL) and erythema are other non-invasive techniques used in the tape-stripping model to study skin barrier function indirectly.<sup>35,36,37</sup> Erythema is primarily a subjective method, which is therefore a limiting measure in skin damage research. Unfortunately, with RCM it was not possible to determine a non-invasive objective method for vascularization, which might have been linked to the degree of erythema in future. Although some limitations of TEWL measurements have been reported,<sup>38,39</sup> combining TEWL and erythema measurements with the currently evaluated non-invasive skin damage model will complement the model by supplying biophysical data in addition to the morphological RCM data. A combination with self-assessment to measure discomfort is important to determine the user friendliness of products and materials.<sup>40</sup>

It should be mentioned that mechanical provocation of the skin not only involves the epidermis. Forces and velocity play also an important role in the caused damage, and are recommended to evaluate in future studies.

In conclusion, the combination of tape stripping with RCM imaging can be used as a non-invasive model to obtain in vivo morphological data on skin-material interactions. In order to improve and develop skin friendlier materials and products, this in vivo model can be used in skin-material testing for exposure to repeated or acute impact. Epidermal thickness, keratinocyte proliferation, parakeratosis, epidermal atypia, and spongiosis are parameters that can be studied over time.



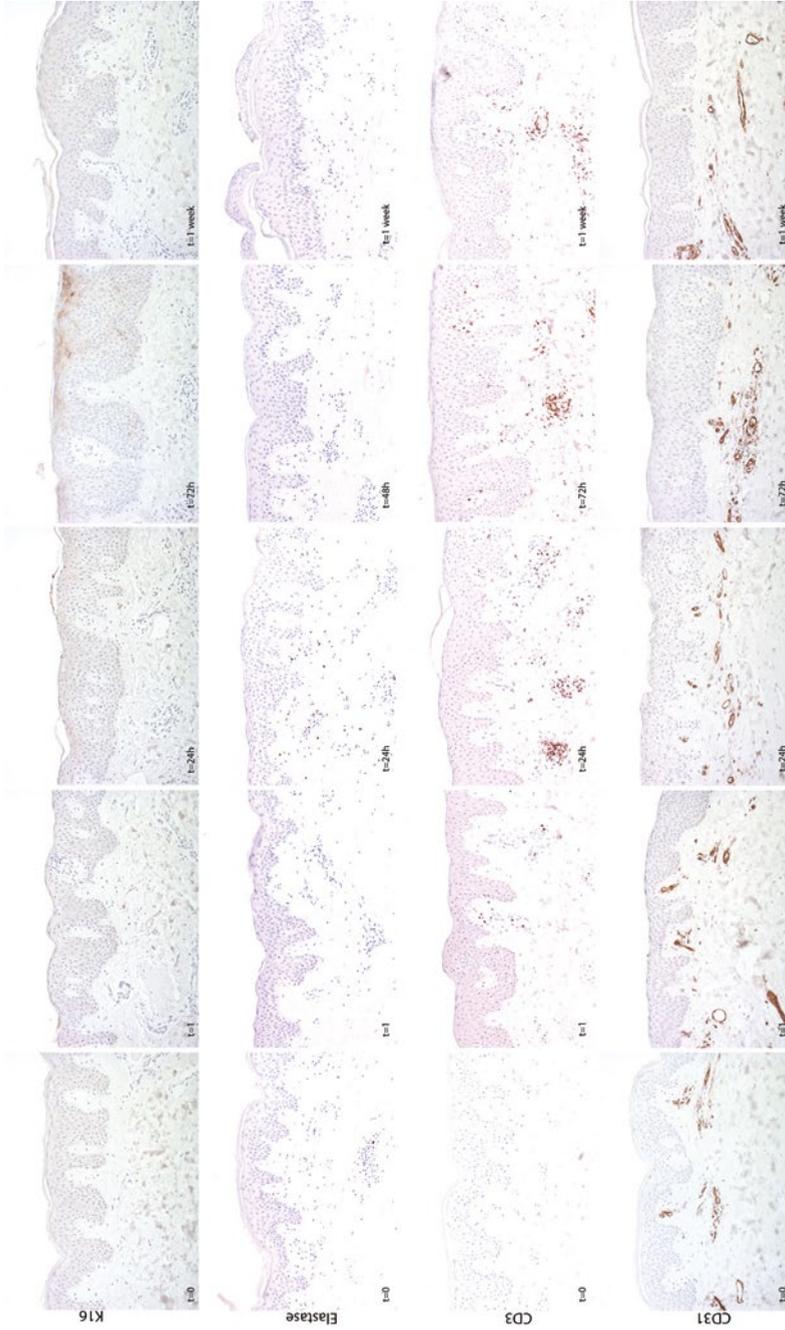
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## Supplementary data



Representative pictures of K16, Elastase, CD3, and CD31 immunohistochemical staining over time after acute tape stripping.





# 3.2

## Exploring the biomechanical load of a sliding on the skin: understanding the acute skin injury mechanism of player-surface interaction

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## Abstract

**Background:** Currently, there is a shortage of biomechanical data regarding acute skin injury mechanisms that are involved in player-surface contact in soccer on artificial turf. It is hypothesized that peak loads on the skin during the landing phase are an important factor in causing an acute skin injury.

**Methods:** Simultaneously, video analysis and load measurements using an in-ground force plate of the landing phase of a sliding tackle were recorded and correlated with observed clinical skin lesions.

**Results:** Video analysis revealed two sliding techniques: a horizontal jump and a sliding-in technique. The first technique resulted in both significantly higher vertical and horizontal peak forces during impact on the knee ( $2.3 \pm 0.4$  kN and  $1.4 \pm 0.5$  kN) and thigh ( $4.9 \pm 0.9$  kN and  $1.8 \pm 0.5$  kN). In combination with the observed skin lesion areas, a combined normal-shear stress of at least 24 and 14 N·cm<sup>-2</sup> induce abrasion injuries on dry artificial turf.

**Conclusion:** The findings of this study confirm that high peak stresses during the landing phase of a sliding is critical for inducing skin injuries on the knee and thigh. Reducing these peak shear stresses could be an important first step towards preventive measures.

## Introduction

The human skin is flexible and has a huge capability to absorb mechanical load. However like any other material, it has its limitations resulting in failure or breakdown. From a biomechanical perspective, an injury is “equivalent to the failure of a machine or structure” and results from an energy transfer to the tissue.<sup>1</sup>

Although sliding induced skin injuries are uncomfortable and unpleasant, these lesions rarely lead to absences from training or soccer matches. Further, medical attention is often not needed.<sup>2</sup> The most commonly used definition of injury, typically based on absences or need for medical attention, determines which data are collected during incidence studies. Using this definition, minor injuries, such as skin abrasions or lacerations, are sporadically documented and therefore underestimated.<sup>3</sup> However, in retrospective studies, it is reported that players suffer more often from abrasion injuries than from other injuries, such as strains, sprains and fractures.<sup>4,5</sup> Players’ perception may also affect their behaviour in the field. Andersson et al. showed that the number of slides performed on artificial turf was lower than on natural grass.<sup>6</sup>

Safety, the possible effect on the game and the perception of players are the main factors to determine quality standards regarding skin abrasions on artificial turf pitches. The currently accepted test method to determine skin abrasions, FIFA test method 8, is based on a rotating test foot with a silicone skin mounted on it.<sup>7</sup> This method is questioned by Sanchis et al., as it does not simulate the realistic vertical forces and velocities of a sliding tackle.<sup>8</sup>

Although the incidence of skin injuries is limited documented in the literature, the injury location is seldom reported. Only Immers et al., who studied 279 amateur soccer players, reported the injury location.<sup>9</sup> The knee seems to be the most vulnerable body part to the occurrence of skin lesions during a sliding.

For development of preventive measures, in order to reduce sliding induced skin injuries on artificial turf, it is important to understand the injury mechanism.<sup>10</sup> Recently, an overview of the skin injury mechanism due to player-surface contact was described.<sup>2</sup> Several studies have been published on the intrinsic risk factors (gender, age and location) and extrinsic risk factors (pitch condition, type of surface, protective equipment and skin lubricants), which could have an effect on the occurrence of skin injuries. Unfortunately, the availability of literature and biomechanical data on the sliding tackle as cause of abrasion injuries is lacking at the moment.

In a study performed by Fuller et al., six different tackling actions were identified.<sup>11</sup> Two tackling actions, the so-called sliding in – one footed tackle and a two footed horizontal jumping tackle, are of interest because these involve skin-surface contact. In a descriptive analysis of a feet-first sliding in baseball, which is similar to a sliding-in tackle in soccer, Corzatt et al. distinguished four phases: sprinting, attainment of sliding position, airborne phase and landing phase.<sup>12</sup> From fall studies it is known that peak forces

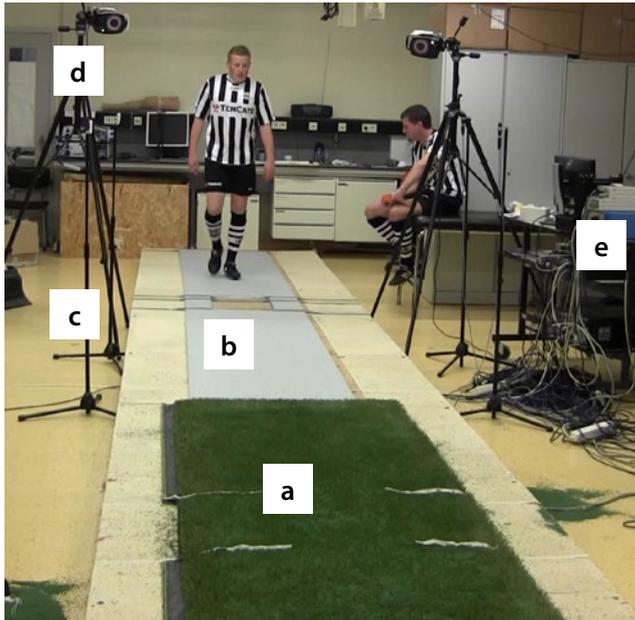
during impact can be in the range of 4 to 8 times body weight.<sup>13,14,15</sup> Unfortunately, these fall-related studies do not report horizontal or shear forces, which are important for causing abrasion- or laceration-type of skin injuries.<sup>16</sup>

In line with these fall studies we hypothesized that the peak loads on the skin of knee and thigh are an important injury mechanism to cause acute skin injuries during player-surface contact.

The main goal of this exploratory study was to provide data of the mechanical load on the skin during the landing phase of a soccer sliding. With the combination of biomechanical data, qualitative analysis of the sliding movement and the observed skin injuries and there location, we aim to broaden the insight on the mechanism of sliding tackle-induced injuries.

## Materials en methods

In total thirty-six sliding tackles were performed by three healthy male soccer players. The sliding tackles were made on a third-generation artificial turf pitch in a laboratory with a force plate (Figure 1). The artificial turf system had a 50-mm fibre length and was



**Figure 1** Set-up of the laboratory experiments with the force plate (a), 10 meter run way (b), light gates to measure the initial velocity (c), video cameras (d) and data analysing equipment (e).

filled with 35-mm commercial Thermoplastic Polyethylene (TPE) granular infill material. According to FIFA method 4, the shock absorption of this artificial turf pitch was determined to be  $56\% \pm 2\%$ , and it has an energy restitution of  $38\% \pm 3\%$ .<sup>17</sup> In addition, the artificial turf pitch meets all of the requirements of FIFA-1-STAR.

The age ranged from 25 to 35, with a mean age of 29 years. Their length varied between 180 and 191 cm and body mass was between 77 and 84 kg resulting in a body mass index between 22 and 26. All players wore short sliding shorts for protection of the skin in the hip region.

In total, each player performed twelve sliding tackles distributed over two days. For each sliding, they were free to choose whether they performed the sliding with the right or left leg. The landing had to take place on the force plate (Kistler Instruments, Switzerland, type 9282E; dimensions  $60 \times 40 \text{ cm}^2$ ) in order to measure the contact forces in three directions during impact. Video images of the sliding tackles were made to determine if the impact on the force plate took place with both the knee and the hip (VICON, Bonita, United Kingdom). The initial speed was assessed using light gates. The average initial speed of each player had to be in the range of  $4.5$  to  $5 \text{ ms}^{-1}$ , with an acceptable variation of  $0.2 \text{ ms}^{-1}$ .

Measurements were excluded from further analysis where landing of both knee and hip did not take on the force plate or where the initial speed was not in the desired range.

This study was approved by the local ethics committee of the Radboudumc, under reference number 2013/153. The experiments, were conducted according to the Helsinki statement. All the participants volunteered to take part in the study and gave their consent after being informed of the objectives, risks and benefits of the research.

Immediately after the last sliding tackle all participants were evaluated for skin injuries by an experienced dermatologist. Observed skin injuries were quantified by the Skin Damage Area and Severity Index (SDASI) scoring system.<sup>18</sup> The SDASI is a psychosensorial assessment tool to measure skin damage and is defined as the sum of the individual damage characteristics by abrasion, erythema and type of exudation multiplied by the involved area score. The range of the SDASI lies between 0 and 60.

The external forces that act on the player during the impact phase impose mechanical stresses and deformation on the skin. These stresses could be of interest in defining failure criteria for the skin. Mechanical stresses are defined as the quotient between the external force and the cross-sectional area of the surface on which the external force acts. In our case the contact area. In the current setup, it was not possible to determine the contact area immediately. Indirectly, the area of the skin lesion ( $A_s$ ) is used as indication of the area of contact. The area of the skin lesion is measured with a transparent sheet containing a grid, the size of the grid was  $5 \text{ mm} \times 5 \text{ mm}$ . The vertical normal ( $\sigma_z$ ), horizontal in plane shear ( $\tau_y$ ) and horizontal out of plane shear ( $\tau_x$ ) stresses are estimated using the following equations:

$$\sigma_z = F_z / A_s \quad (1)$$

and

$$\tau_y = F_y / A_s \quad (2)$$

and

$$\tau_x = F_x / A_s \quad (3)$$

Finally, the impulse during the landing phase is calculated to see whether there exists differences in change in momentum between players using the following equation:

$$\int_{t_i}^{t_f} \vec{F} dt \quad (4)$$

where:

$\vec{F}$  = instantaneous ground reaction force during impact in Newton (N),

$t_i$  = initial time of impact in seconds, defined as the time when the ground reaction force first exceeds the participant's body weight,

$t_f$  = final time of impact in seconds, defined as the first time when the ground reaction force is lower than the participant's body weight after the impact of the hip.

The results of the kinetic experiments were analysed using one-tailed analysis of variance (ANOVA) with respect to possible differences between participants. All analysis were performed with SPSS 18.0 for Windows.

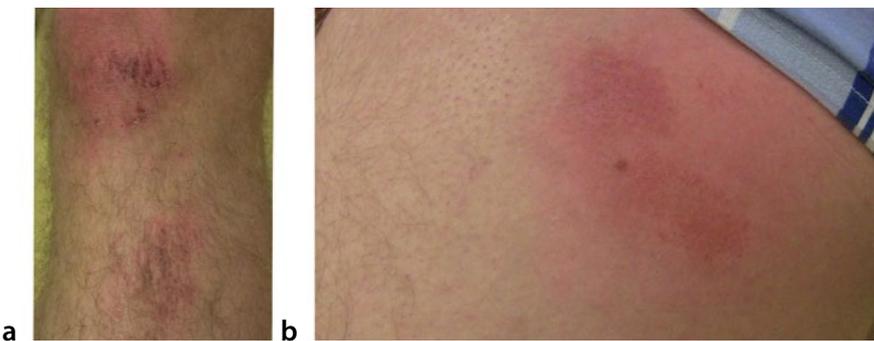
## Results

The qualitative analysis of the sliding tackle videos showed that a typical sliding tackle consisted of three phases: a free fall stage after takeoff, an impact phase of the knee and hip, and finally a gliding phase. In this study, we distinguished between two different sliding techniques. The first technique can be characterized as a horizontal jump. The free fall phase starts almost at hip height. We termed this an offensive sliding tackle. The second technique was more controlled and could be characterized as a sliding-in technique. In this technique, a right-sided tackle first starts with a side step of the left leg, which is slightly bend. The bended right leg then moves below the upper body and makes contact with the surface. In this last technique, the free fall height is substantially lower. We named this a defensive sliding tackle. The video analysis showed that participant 1 performed an offensive sliding technique. The other two participants performed a defensive sliding tackle.

After the experiments, the participants were screened for possible skin injuries. In Table 1 the SDASI scores of all participants are summarised. It is shown that skin lesions on the

**Table 1** Results of the skin injury evaluation by the SDASI. Abrasion from 0 (no abrasion) to 4 (very severe abrasion), Erythema from 0 (no erythema) to 4 (very severe erythema), Type of exudation is classified into no exudation (0), exudation of a transparent fluid (1) or exudation of blood (2), the relatively involved area is defined as the  $A_s/60 \text{ cm}^2 \times 100 \%$ . The following numerical value is given to the relative involved area: 0=no involvement; 1=  $\leq 10\%$ , 2=  $\geq 10\%$  but  $< 30\%$ , 3=  $\geq 30\%$  but  $< 50\%$ , 4=  $\geq 50\%$  but  $< 70\%$ , 5=  $\geq 70\%$  but  $< 90\%$  and 6=  $\geq 90\%$ .

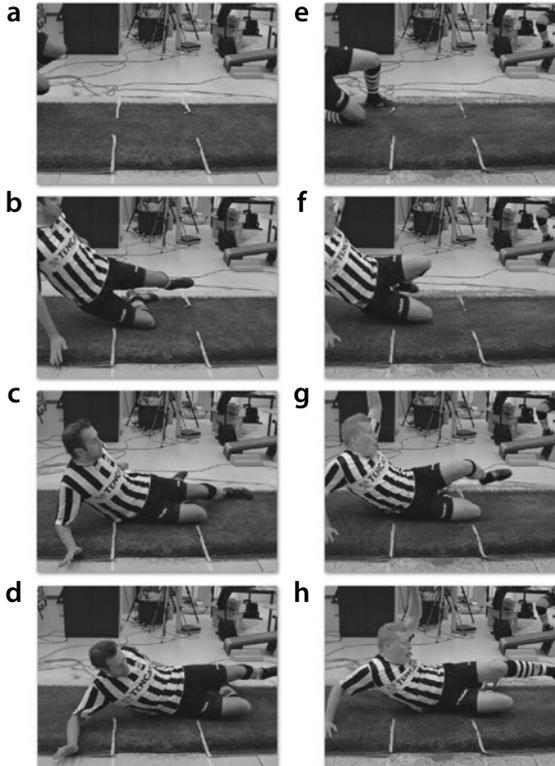
Participant	Position	Abrasion score	Erythema score	Type of exudation score	Involved area [cm <sup>2</sup> ]	Relative involved area	Relative area score	SDASI score
1	Knee	4	4	1	20	34%	3	27
1	Thigh	0	1	0	52	87%	5	5
2	Knee	3	3	0	38	63%	4	24
2	Thigh	0	1	0	57	95%	6	6
3	Knee	4	4	0	41	68%	4	32
3	Thigh	0	2	0	54	90%	6	12



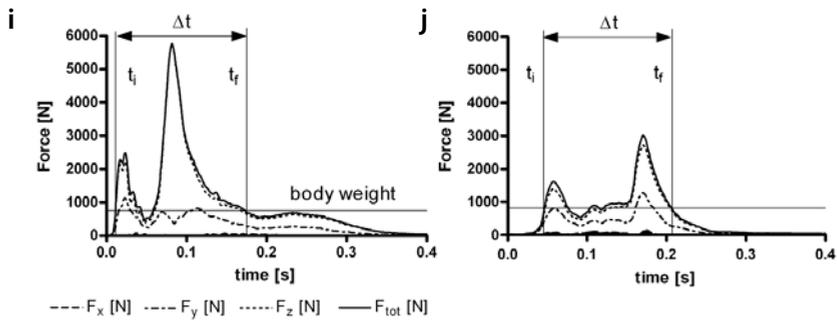
**Figure 2** Representative clinical pictures of sliding induced skin lesions. **a)** Skin lesion at the knee and under leg demonstrating severe abrasion and erythema. **b)** Skin lesion at the thigh showing mild erythema.

knee are characterised by severe abrasion and severe erythema. Only wound exudation, was noticed on the knee of participant 1. Due to the sliding shorts, no signs of abrasion were noted on the thigh, only moderate erythema was observed (Figure 2). Therefore, higher SDASI scores on the knee (24 to 32) were found compared to the thigh (5 to 12).

The characteristic force measurements of an offensive (participant 1) and defensive (participant 2) sliding tackle are summarized in Figure 3. Both techniques demonstrated two clear peaks. The first peak represents the impact on the knee, and the second peak represents the impact on the hip. The time interval ( $\Delta t$ ) of impact is calculated and also illustrated in the graph.



**Figure 3** Position of the force plate and characteristic phases of an offensive (**a, b, c, d**) and defensive sliding tackle (**e, f, g, h**). An offensive sliding tackle or horizontal jump starts with a free fall (**a**) sequenced by the impact of the knee at  $t_1$  (**b**), impact of the hip (**c**) and initiation of the gliding phase at  $t_2$  (**d**). The right sided defensive sliding tackle or sliding-in technique starts with a side step of the left leg where the right leg moves below the upper body (**e**) followed by the impact of the knee at  $t_1$  (**f**), impact of the hip (**g**) and initiation of the gliding phase at  $t_2$  (**h**). Finally, the corresponding contact force measurements of an offensive sliding tackle (**i**) and a defensive tackle (**j**) are shown. The time interval of impact is indicated by  $\Delta t$ , where  $t_1$  and  $t_2$  mark the initial and final points in time of the impact. The following abbreviations were used:  $F_x$  = out-of-plane component of the impact force,  $F_y$  = horizontal component of impact force,  $F_z$  = vertical component of impact force and  $F_{tot}$  = total force of impact force.



**Figure 3** Continued.

Force measurements and calculated stresses are summarized in Table 2. With respect to the sliding tackle technique, an offensive sliding tackle resulted in higher vertical (Z-direction) peak forces of both the knee and hip,  $2.3 \pm 0.4$  kN and  $4.9 \pm 0.9$  kN, respectively. This corresponded to 3.0 – 6.5 times the body weight. In comparison, the maximum vertical load during the gliding phase is restricted to the participant's body weight.

An offensive sliding technique, compared to a sliding-in technique, results in significantly higher horizontal (Y-direction) peak forces on both the knee ( $1.4 \pm 0.5$  kN vs  $0.7 \pm 0.2$  kN) and hip ( $1.8 \pm 0.5$  kN vs  $1.3 \pm 0.2$  kN).

The forces out of plane (X-direction) were negligible compared to the vertical and horizontal forces (Y-direction).

**Table 2** Analysis of variance results of the out of plane (X), vertical (Z) and horizontal (Y) peak forces and corresponding stresses during the impact of the knee and hip, time interval of impact ( $\Delta t$ ) and corresponding impulse of the impact of participants 1, 2 and 3. (mean  $\pm$  SD).

Kinetic Parameters	Participant				F	p
	1 (n=8)	2 (n=5)	3 (n=5)			
$V_i$ [m s <sup>-1</sup> ]	4.54 $\pm$ 0.17	4.51 $\pm$ 0.14	5.00 $\pm$ 0.16		15.53	0.000
$F_{x, knee}$ [N]	-7.3 $\pm$ 22	17 $\pm$ 49	84 $\pm$ 2		0.33	0.723
$F_{y, knee}$ [N]	1456 $\pm$ 460	789 $\pm$ 253	579 $\pm$ 155		11.29	0.001
$F_{z, knee}$ [N]	2307 $\pm$ 401	1240 $\pm$ 530	982 $\pm$ 297		18.79	0.000
$T_{x, knee}$ [Ncm <sup>-2</sup> ]	-0.4 $\pm$ 10	0.4 $\pm$ 1.3	2.0 $\pm$ 0.0		0.17	0.841
$T_{y, knee}$ [Ncm <sup>-2</sup> ]	71 $\pm$ 21	21 $\pm$ 7	14 $\pm$ 4		28.97	0.000
$\sigma_{z, knee}$ [Ncm <sup>-2</sup> ]	115 $\pm$ 19	33 $\pm$ 14	24 $\pm$ 7		77.68	0.000
$F_{x, hip}$ [N]	243 $\pm$ 354	-31 $\pm$ 112	242 $\pm$ 70		2.13	0.152
$F_{y, hip}$ [N]	1839 $\pm$ 458	1269 $\pm$ 151	1347 $\pm$ 280		5.08	0.021
$F_{z, hip}$ [N]	4983 $\pm$ 897	3122 $\pm$ 317	2924 $\pm$ 455		18.78	0.000
$T_{x, hip}$ [Ncm <sup>-2</sup> ]	3.1 $\pm$ 6.8	-0.5 $\pm$ 2.0	4.5 $\pm$ 5.0		1.32	0.294
$T_{y, hip}$ [Ncm <sup>-2</sup> ]	34 $\pm$ 8.8	22 $\pm$ 3	25 $\pm$ 20		5.26	0.017
$\sigma_{z, hip}$ [Ncm <sup>-2</sup> ]	90 $\pm$ 20	55 $\pm$ 6	54 $\pm$ 32		14.18	0.000
$\Delta t$ [s]	0.16 $\pm$ 0.02	0.159 $\pm$ 0.01	0.15 $\pm$ 0.01		0.35	0.707
total impulse impact [Ns]	287.1 $\pm$ 40.9	215.5 $\pm$ 22.9	183.4 $\pm$ 23.8		17.16	0.000

\* participants separated with "/" are significantly different. Participants separated with "-" are not significant

## Discussion

In the present explorative study, video and load measurements of the landing phase of a sliding tackle were recorded simultaneously. Two peak forces, corresponding with the impact of the knee and the hip were registered. Injury screening showed severe abrasion and severe erythema on the knee and mild erythema on the hip. Video analysis of the sliding tackles revealed that the knee was only in contact with the surface during the landing phase. These preliminary findings confirm our initial hypothesis that the landings phase and corresponding peak loads play an essential role in causing acute skin injuries. Reducing these peak loads, for example, by reducing the coefficient of friction could be a first step towards preventive measures.

The measured vertical peak forces on the thigh correspond to the values reported in other fall studies.<sup>13,14</sup> Schmitt et al., who studied the impact forces on the hip during side jumps performed by goalkeepers, found vertical peak forces varying from 3 to 8 kN.<sup>15</sup>

The reason for the significant higher loading during an horizontal jump compared to a sliding-in technique is most likely due to the difference in free fall height, resulting in a higher impact energy with the assumption of equal initial velocity. Although the derived stresses are estimates, the vertical peak stresses on the thigh are in the same rate as described in literature.<sup>15</sup>

Dependent of the sliding technique differences in clinical findings in involved area and exudation were observed. Wound exudation and smaller wound area was noticed on the knee of participant 1 who performed a higher kinetic horizontal jump technique. This corresponds to a deeper wound compared to a sliding-in technique where no wound exudations were found. Despite the difference in sliding techniques and corresponding significant differences found in kinetic parameters both techniques resulted in severe abrasions and comparable SDASI scores on the knee. This implies that the loads measured during the knee impact are above the skin injury threshold. Therefore, a preliminary finding of this study is that a combined normal-shear stress load of at least 24 and 14 Ncm<sup>-2</sup> is sufficient to induce abrasion type of skin injuries during a sliding on dry artificial grass. It must be remarked that the injury screening took place after 12 sliding tackles. No information was obtained of the moment when the skin injury was induced. There could be a strengthening effect of the repeated impact loads.

To the best of our knowledge, in fall studies, no critical skin failure stress data has been published in relation to abrasion type of skin injuries. Studies on the skin breakdown mechanism of superficial pressure ulcers provide some reference data. In an *in vivo* pig model, it has been shown that skin breakdown occurs when applying a combined normal-shear stress load of 10 and 7 Ncm<sup>-2</sup>, respectively.<sup>19</sup> Interestingly, these repetitive mechanical stress experiments have also shown that skin breakdown occurs earlier when shear stress increases. Therefore, reducing horizontal peak stresses during the landing could be important in preventing abrasion type of skin injuries.

It must be noted that Goldstein's skin breakdown criteria are based on a 10 minute repetitive combined loading test at  $0.035 \text{ ms}^{-1}$ , which is much slower than an acute impact loading of a sliding. Besides the nature of the load and its velocity also other intrinsic factors such as age, gender, body location and extrinsic factors as temperature, humidity or surface roughness plays a role in how and when skin failure occurs. It must be emphasized, that present literature lacks suitable values for abrasion injury risk.

### **Conclusions**

In conclusion, this study presents the results of kinetic experiments of the sliding tackle movement on artificial turf. The high impact forces and stresses, in combination with the corresponding locations of observed abrasions, indicate that the impact phase is critical for inducing skin injuries.

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# 3.3

## The load tolerance of skin during impact on artificial turf using ex-vivo skin as the readout system

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## Abstract

Understanding the mechanism of sliding induced skin injuries on artificial turf is important to define preventive measures. Recent findings revealed that high peak loads on the knee and thigh during impact of a sliding tackle are critical for inducing skin injuries. Unfortunately, skin failure data under combined impact load is lacking.

In this study the load tolerance of skin to impact on both dry and wet artificial turf and natural grass is investigated by developing an *ex-vivo* model, a biaxial load applicator and a loading protocol.

The critical shear-normal stress combination at which skin breakdown occurred on dry artificial turf was 38 and 20 Ncm<sup>-2</sup>. Skin damage on wet artificial turf firstly was noticed at a shear-normal stress combination of 55 and 20 Ncm<sup>-2</sup>. On natural grass, skin breakdown only occurred at a combined shear and normal stress of 130 and 125 Ncm<sup>-2</sup>. The thickness of the stratum corneum strongly correlated to the applied mechanical load during impact on dry artificial turf.

In contrast to natural grass, skin damage on dry artificial turf is strongly related to the magnitude of the impact load. Wetting of the artificial turf system improves the load tolerance of skin to impact.

## Introduction

The benefits of artificial turf over natural grass such as lower maintenance costs compared with natural grass and high playing intensity and consistency are generally recognized.<sup>1</sup> However, artificial turf is still strongly associated with abrasion type injuries. Survey studies revealed that players are complaining more about abrasion type injuries than any other type of injuries.<sup>2,3,4</sup> Improving the sliding comfort and abandoning unpleasant sport surfaces, related to skin injuries, have therefore been of interest for manufacturers and sport governing bodies. In order to reach these goals, a better understanding of the mechanisms behind skin injury is needed.

Current test methods for assessing the abrasiveness of artificial turf use skin replacers like silicon or foam as a readout.<sup>5,6</sup> However, these methods are questioned because they do not simulate the real load experienced by a player during a sliding.<sup>7</sup> Further, the applied materials do not mimic the real skin response.<sup>8</sup>

A sliding movement consists of three phases: a free drop phase, an impact phase and a gliding phase.<sup>9</sup> The existing test methods to evaluate the abrasiveness of soccer pitches focus on the gliding phase, where relatively low contact loads and large displacements are applied. Biomechanical fall studies focusing on the impact on the hip during side jumps by soccer goalkeepers showed that during impact, loads of 4.2 to 8.6 times body weight are common. Such loads correspond with normal stresses ranging from 87 to 187 Ncm<sup>-2</sup>.<sup>10</sup> Recent studies on the landing phase of a sliding movement reveal that the high peak stresses on the knee and thigh during impact are critical in inducing skin injuries. In their exploratory study Van den Eijnde et al. estimated that a combined shear and normal stress of at least 14 and 24 Ncm<sup>-2</sup> at impact velocities of approximately 3 ms<sup>-1</sup> can induce a skin abrasion injury on dry artificial turf.<sup>11</sup>

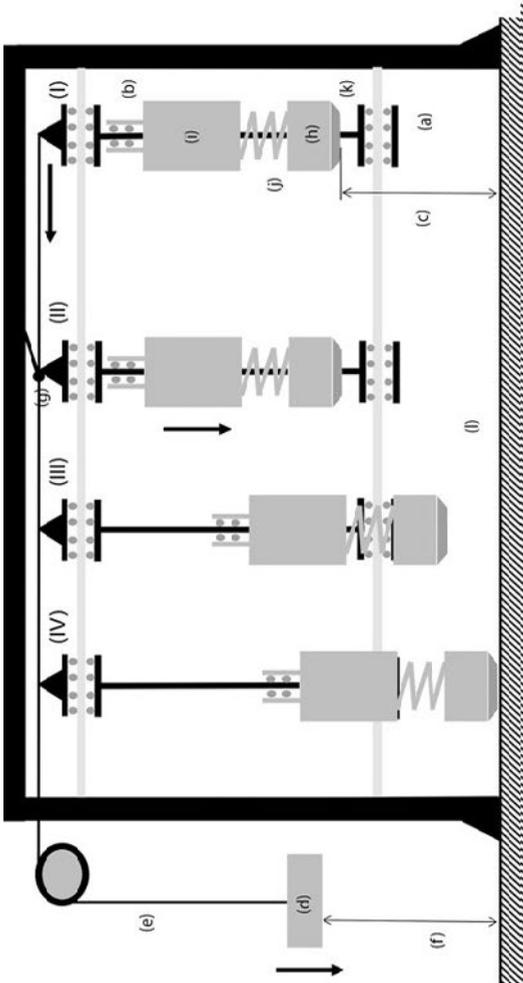
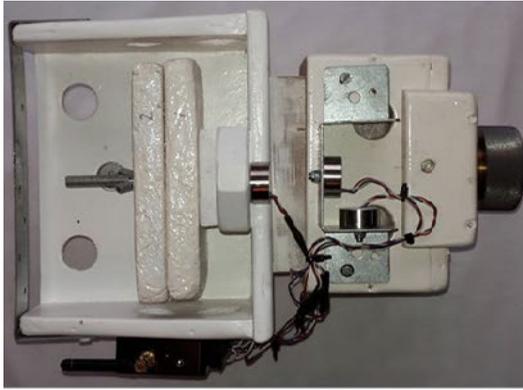
To the best of our knowledge, no critical skin failure stress data has been published in relation to fall studies and abrasion type of skin injuries. The aim of our study is to investigate the load tolerance of skin to impact on both dry and wet artificial turf and natural grass by developing an *ex-vivo* model, a biaxial load applicator and a loading protocol. It is postulated that the skin response and possible skin damage is strongly related to the magnitude of the impact load and its resulting stresses.

## Materials and Methods

### Biaxial load applicator

The biaxial load applicator (Figure 1) was designed to launch an impact body on a surface with both vertical and horizontal velocity component.

To accomplish the combined horizontal and vertical translation, the impact body is placed on a horizontal (Figure 1, a) and a vertical rail (Figure 1, b). The impact height of the



**Figure 1** Schematic illustration of the biaxial load applicator during the four sequential phases: (I) starting position of the horizontal translation, (II) start of the free drop phase induced by an electromagnetical switch, (III) free horizontal and vertical translation phase and (IV) the impact phase. (left). Photo of the impact body including the positioning of the accelerometers, wireless inputs node and clamping system (right).

impact body (Figure 1, c) can be adjusted to a maximum of 0.5 m, which corresponds to a maximum velocity of  $3.0 \pm 0.2 \text{ ms}^{-1}$  which is derived from the vertical accelerometer. The impact body is set in horizontal motion by releasing a deadweight (Figure 1, d) of 2.5 kg at the left hand side of the apparatus.

The horizontal velocity of the interconnected (Figure 1, e) impact body can be adjusted by setting the drop height of the deadweight (Figure 1, f) to a maximum of 0.57 m. The corresponding maximum horizontal velocity is  $1.9 \pm 0.2 \text{ ms}^{-1}$  which is derived from the horizontal accelerometer. The vertical drop is initiated when the impact body passes an electromagnetic switch (Figure 1, g) that is positioned on the horizontal rail. The position of the switch can be adjusted and depend on the drop height of the deadweight allowing a free fall of the impact body.

The impact body consists of a mass-spring configuration, which resembles the human body impact. The configuration is able to absorb energy during impact, resulting in a longer contact time compared to a single rigid body impact.<sup>12</sup> The typical impact time of the knee during a sliding on artificial turf, derived from biomechanical tests, is  $30 \pm 5 \text{ ms}$ .<sup>11</sup> The lower mass (Figure 1, h) has a weight of  $1.15 \pm 0.02 \text{ kg}$  and the upper mass (Figure 1, i) can be adjusted from  $1.15 \pm 0.02 \text{ kg}$  in steps of 0.47 kg to a maximum of  $3.5 \pm 0.04 \text{ kg}$ . In this study the upper mass is held constant at  $2.09 \pm 0.02 \text{ kg}$ . The two masses are interconnected with a spring (Figure 1, j), which has a spring constant of  $10 \pm 0.5 \text{ Nmm}^{-1}$ . The clamping system (Figure 1, k) for the *ex-vivo* skin is similar to the specimen holder used in the Martindale test (ASTM D4966-98), for testing the abrasion resistance of textile fabrics.<sup>13</sup> The contact area of the skin is  $8 \text{ cm}^2$ . The tested surfaces (Figure 1, l) are mounted on to the outer frame of the apparatus.

### Instrumentation (Load measurement)

The biaxial load applicator contained three capacitive spring-mass accelerometers (type B3, Seika.de, Germany) with a range of -50 g to 50 g and corresponding resolution of  $< 2 \cdot 10^{-2} \text{ g}$  and a linearity deviation of  $< 0.5 \%$  adjusted on the impact body (Figure 1, right). The accelerometers are connected to a wireless 7 channel analog input sensor node (type V-link-LXRS, Lord MicroStrain, USA). A USB data gateway (type WSDA-Base-104-LXRS, Lord MicroStrain, USA) collects the synchronized data from the wireless sensor node. Data logging software (Node Commander, Lord MicroStrain, USA) is used for node programming, data acquisition and data analyses at a sampling rate of 800Hz. The accelerometer data is used to derive the velocity, reaction forces and corresponding peak stresses in both directions of the impact body (Supplementary information).

To verify the repeatability of the vertical and horizontal reaction force signals, a calibration setup is used consisting of a force plate (Kistler Instruments, Switzerland, type 9282E; dimensions  $60 \times 60 \text{ cm}^2$ ) and a mounted spring. The spring constant of the mounted spring was  $26 \pm 0.5 \text{ Nmm}^{-1}$ . Different impact conditions per impact direction were applied. Three drop heights of deadweight (Figure 1, f) 10, 30 and 47 cm, resulted in

three horizontal impact conditions. In addition, three drop heights of the impact body (Figure 1, c) 3, 10 and 20 cm, resulted in three different vertical impact conditions. These tests were repeated three times to finalize calibration.

### Testing surfaces and conditions.

Two different playing surfaces were tested, natural grass and a third generation artificial turf system. The artificial turf system was tested both dry and wet. The wet condition was obtained by manually spraying, in total with 0.4 l m<sup>-2</sup> water. The artificial turf system, with a size of 120 x 50 cm<sup>2</sup>, had a monofilament type of polyethylene fibre with a length of 50 mm and contained 35 mm commercial Thermoplastic Polyethylene (TPE) infill material with a granulometry from 0.5 to 2 mm and bulk density of 0.38 kg m<sup>-2</sup>. According to the FIFA method 4, the shock absorption of this artificial turf pitch was determined to be 56 ± 2 % and had an energy restitution of 38 ± 3 %.<sup>14</sup> Additionally, the artificial turf pitch met all requirements for FIFA-1-STAR. The natural grass with a size of 50 x 50 cm<sup>2</sup> was cultivated and constructed according to DIN 18035-4. The total thickness of the grass sod was 75 ± 5 mm and the grass length was 40 ± 5 mm.

Nine different impact conditions were used per surface condition. The load protocol is summarized in Table I. All tests were performed under laboratory conditions at 50 ± 5 % relative humidity and 20 ± 2 °C.

**Table 1** Load protocol per surface condition with the corresponding settings of the biaxial load applicator regarding the drop height of the deadweight (Figure 1, f) and impact body (Figure 1, c).

Test run	f [cm]	c [cm]
1-2	57 ± 0.3	20 ± 0.3
3-4	29 ± 0.3	20 ± 0.3
5-6	10 ± 0.2	20 ± 0.3
7-8	57 ± 0.3	10 ± 0.2
9-10	29 ± 0.3	10 ± 0.2
11-12	10 ± 0.2	10 ± 0.2
13-14	57 ± 0.3	3 ± 0.2
15-16	29 ± 0.3	3 ± 0.2
17-18	10 ± 0.2	3 ± 0.2

## Ex-vivo skin model as readout

In this study rabbit ears were used as *ex-vivo* model. The ears were obtained from a slaughterhouse in Gent (Belgium) and were conserved at 5 °C for a maximum of 48 hours. The skin samples were cut from the ears using a circular cutting punch with a diameter of 38 mm.

To study the skin morphology, samples (15 x 5 mm<sup>2</sup>) were taken perpendicular to the horizontal load direction immediately after impact. After fixation in 4 % formalin the skin samples were embedded in paraffin. Paraffin sections (6 µm), cut by microtome (Leica, Microsystems SP 1600, Nussloch, Germany), were deparaffinized with histosafe (Adamas, Rheden, The Netherlands) followed by rehydration in decreasing concentrations of alcohol (100-50%). The sections were hematoxyline-eosin (HE) stained for morphological assessment. In total, two HE stained sections per test condition were used for analyses.

The HE stained tissue sections were examined using a microscope (Axioskop2 MOT; Zeiss) equipped with a digital photo camera (AxioCam MRC5; Zeiss) with a resolution of 2584 x 1936 pixels and AxioVision software (Zeiss). With the used magnification we were able to examine a field of view of 2.8 x 2.1 mm<sup>2</sup>. From each HE stained section two images were taken on different locations.

First, the microscopic images were visually assessed on the presence of epidermal skin damage. Furthermore, quantitative analyses were performed using image software (ImageJ 1.49v, National Institutes of Health, USA) to calculate the average thickness of the stratum corneum. Per microscopic image, the average thickness of the skin sample was determined on three different locations covering the full length of the skin section.

## Statistics

The Pearson correlation coefficient was used to study the relationship between the measured stratum corneum thickness and the calculated mechanical parameters. Correlations coefficients between 0 and 0.3 (0 and -0.3) indicate a weak relationship, values between 0.3 and 0.7 (-0.3 and -0.7) indicate a moderate relationship and values between 0.7 and 1 (-0.7 and -1) indicate a strong relationship. All analyses were performed with SPSS 23.0 for Windows.

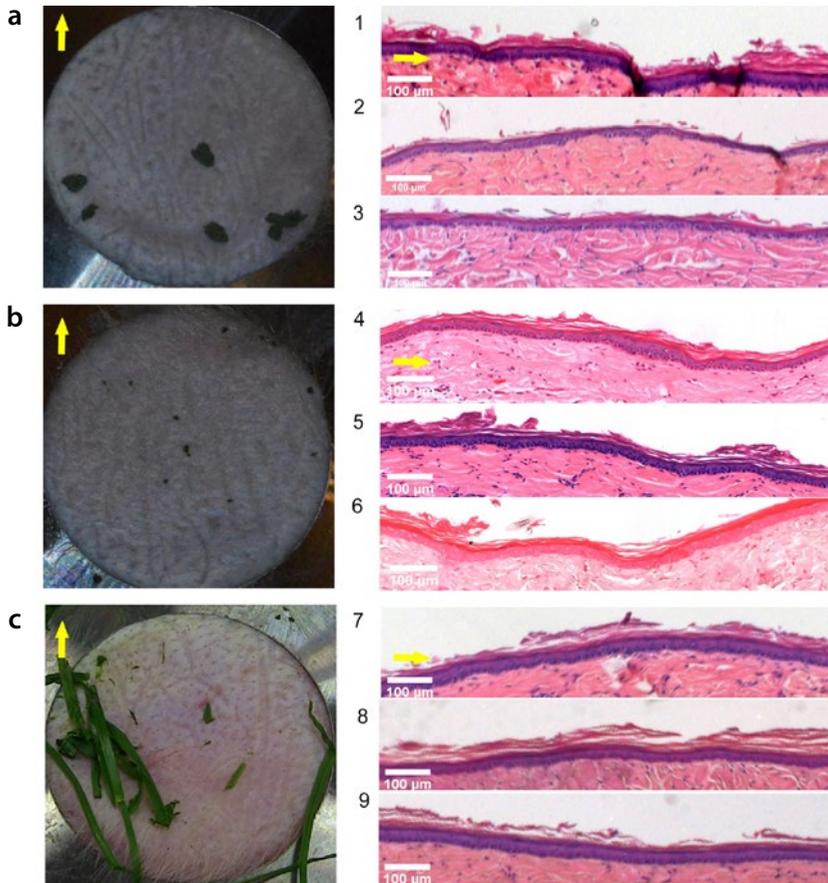
## Results

### Validation and calibration of the apparatus

The performance of the biaxial load applicator had acceptable levels of repeatability with respect to the measured peak forces as illustrated in Table 2. Both horizontal and vertical peak forces were properly reproduced. Comparison of the peak forces of both the force plate and accelerometer data of the biaxial load applicator revealed that the force measurements of the biaxial load applicator are within 10 % accuracy.

**Table 2** Assessment of repeatability using a force plate with mounted spring set up and derived force data of the accelerometers of the biaxial load applicator at three vertical impact conditions and three horizontal impact conditions.

Peak Force	Impact condition [cm]	Force plate			Accelerometer			Deviation	
		Average [N]	SD [N]	Repeatability [%]	Average [N]	SD [N]	Repeatability [%]	Absolute [N]	Relative [%]
Vertical	3	254	1.8	0.7	273	3.18	1.2	18	7
	10	413	2.3	0.5	387	11.0	2.8	-26	-6
	20	541	24.9	4.6	562	21.8	3.9	21	4
Horizontal	10	78	4.8	6.2	86	7.47	8.7	8	10
	30	222	7.9	3.6	206	2.0	1.0	-16	-7
	47	301	3.9	1.3	304	19.0	6.2	3	1

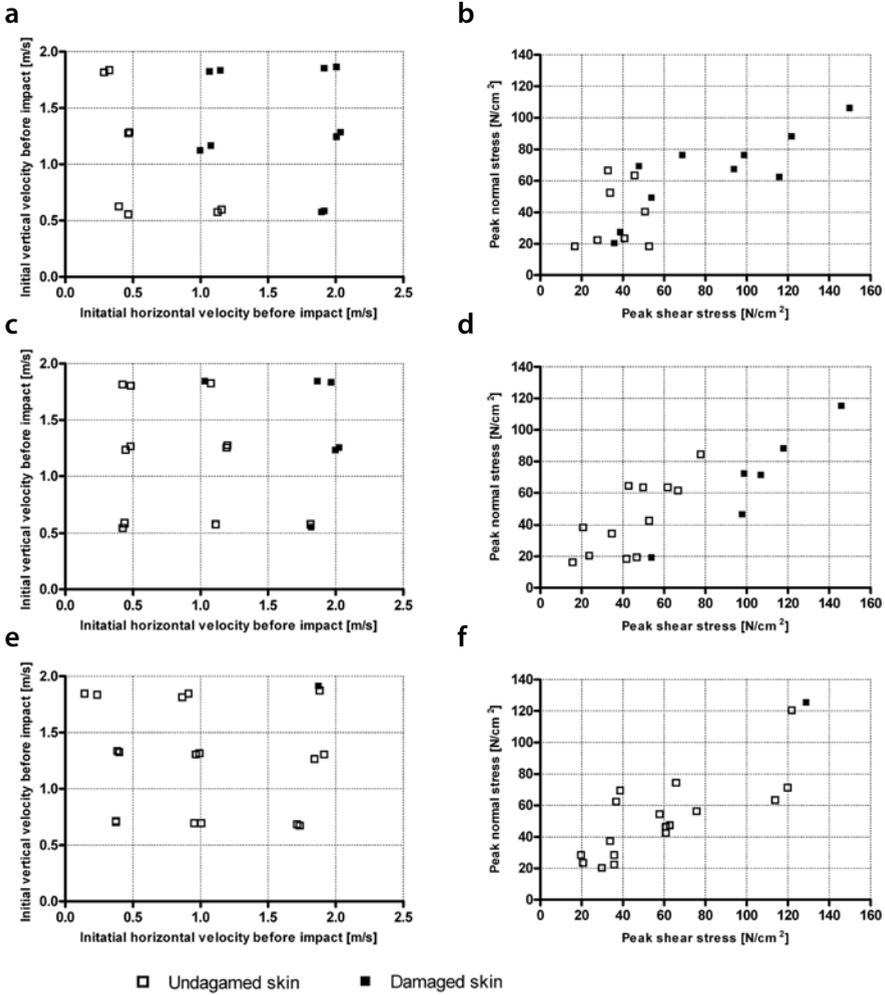


**Figure 2** Macroscopic images of the rabbit ear immediate after test run 1 on dry artificial turf (a), wet artificial turf (b) and natural grass (c). The right column consecutively represents the skin histology after test runs 18, 9 and 1 on dry artificial turf (1, 2, 3), wet artificial turf (4, 5, 6) and natural grass (7, 8, 9), respectively.

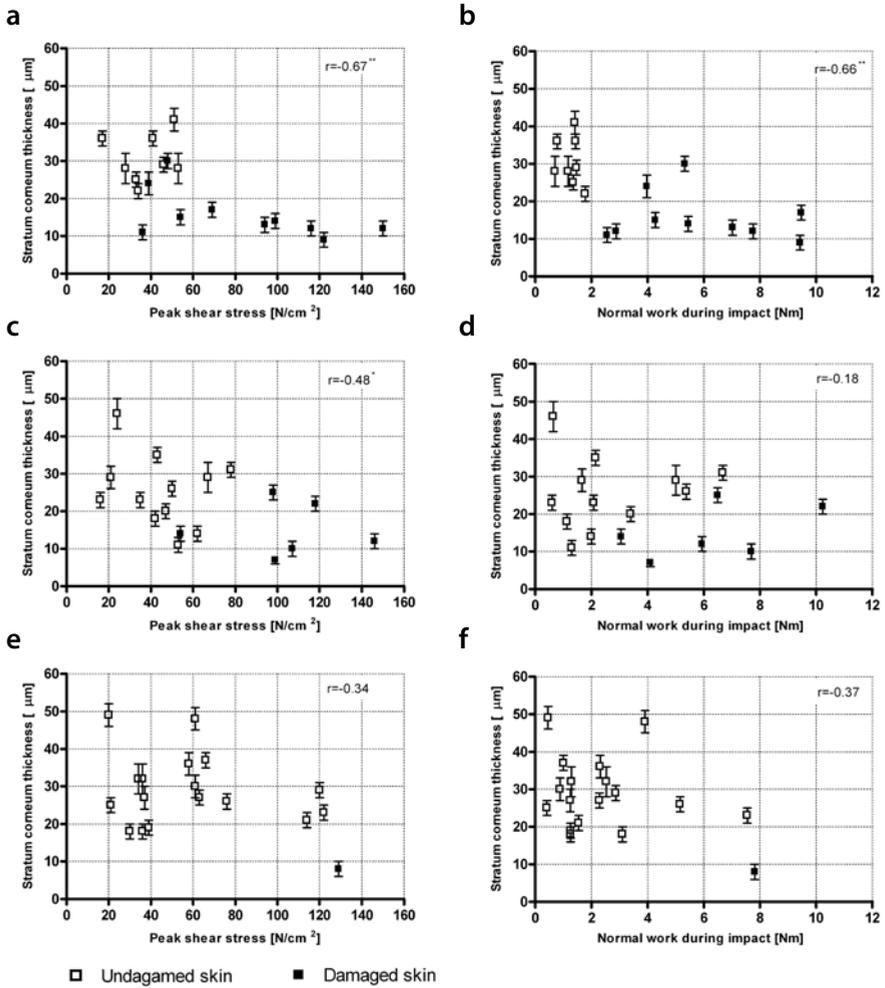
### Qualitative observations

Visual inspection of the skin samples tested on both dry and wet artificial turf showed a pattern of sharp grooves and pits (Figure 2). The grooves are mainly orientated parallel to the sliding direction. This pattern was seen after every run. After run 1 and 2 on both wet and dry artificial turf, it was noticed that infill was left behind on the skin.

Skin samples tested on natural grass showed a pattern of grooves after run 1 to 8. These grooves were less clear compared to the tests on artificial turf. After run 1, 2, 7 and 8, pieces of grass were present on the skin and the skin was stained green.



**Figure 3** Visual assessment of microscopic skin damage analyses in relation to the different impact velocity combinations and in relation to the resulting peak stresses on dry artificial turf (a-b), wet artificial turf (c-d) and natural grass (e-f).



**Figure 4** Correlation between the peak shear stress, the normal work during impact and the stratum corneum thickness on dry artificial turf (a-b), wet artificial turf (c-d) and natural grass (e-f).

Assessment of the microscopic images revealed that the stratum corneum of the skin samples subjected to dry and wet artificial grass were disrupted and damaged after test run 1 to 10 and 1 to 7, respectively. Skin samples subjected to natural grass showed no signs of damage or disruption, except for test run 2.

### Quantitative observations

The results of the visual microscopic assessment and both the measured impact velocities and peak stresses are shown in Figure 3. It is seen that the nine conditions resulted in nine different reproducible combinations of horizontal and vertical impact velocities.

The different impact conditions resulted in combined peak shear and normal stress levels ranging from 18 N·cm<sup>-2</sup> up to 150 N·cm<sup>-2</sup>. The shear-normal peak stresses as well as the measured impact velocities on all test surface conditions are comparable.

The results show that skin breakdown on dry artificial turf occurs at lower impact velocity combinations compared to the wet condition and natural grass. Skin breakdown on dry artificial turf occurred at a shear-normal stress combination of 38 and 20 N·cm<sup>-2</sup>. In the wet condition, skin breakdown firstly occurred at a shear-normal stress combination of 55 and 20 N·cm<sup>-2</sup>. On natural grass skin breakdown only occurred at a shear-normal stress combination of 130 and 125 N·cm<sup>-2</sup>.

The stratum corneum thickness measurements on skin subjected on dry artificial turf revealed that the stratum corneum thickness strongly correlated (Figure 4) with the horizontal velocity component ( $r = -0.649$ ,  $p = 0.04$ ), the kinetic energy before impact ( $r = -0.665$ ,  $p = 0.03$ ), normal work during impact ( $r = -0.714$ ,  $p = 0.01$ ), normal peak stress ( $r = -0.555$ ,  $p = 0.17$ ) and shear peak stress ( $r = -0.678$ ,  $p = 0.02$ ). In the wet condition, only a moderate correlation was found with the shear peak stress ( $r = -0.479$ ,  $p = 0.44$ ). No significant correlations were found with respect to the thickness of the stratum corneum and the mechanical parameters for skin tested on natural grass.

## Discussion

Essential biomechanical data in the field of the tolerance of skin to impact with sport surfaces are lacking at the moment. With the aid of a newly developed biaxial load applicator and using rabbit ears as a model for human skin, it was possible to systematically evaluate skin damage over a range of impact loads and stresses. It was found that skin damage on dry artificial turf is strongly related to the magnitude of the impact load, whereas this relationship was not observed for natural grass. It was also found that the load tolerance of skin during impact on dry artificial turf is lower compared to a wet artificial turf condition and natural grass. This is in accordance with player perception studies, where players complain more about the abrasiveness of artificial turf than natural grass.<sup>4</sup> The results are also in line with the clinical findings described by Peppelman et al.

where soccer slidings performed on artificial turf resulted in more abrasions than on natural grass.<sup>15</sup>

By macroscopic visual assessment, we have shown a specific pattern of sharp grooves and pits on the skin samples tested on artificial turf. It is plausible that the pits are caused by the indentation by the infill material during contact. The grooves have the same width and depth as the pits. Zanetti et al. has already shown that the perceived abrasiveness is influenced by the type of infill: with regards to abrasion, players prefer Styrene Butadiene Rubber (SBR) over Thermoplastic Elastomer (TPE) infill.<sup>2</sup> For future research it would be interesting to compare different types of infill and even non-infill systems to determine the influence on the load tolerance of skin by using the developed biaxial load applicator.

At higher loads, the skin samples tested against natural grass stained green and showed a less sharp, less dense and less deep groove like pattern compared to skin tested against artificial turf. The green staining most likely comes from the chlorophyll pigment present in the plants chloroplasts. The local failure of grass blades together with the plants chloroplasts functioning as a sort lubricant are important beneficial properties of natural grass over artificial turf in reducing the risk of abrasion injuries.

The possibility to control many variables, which cannot be controlled in humans *in vivo*, is a major advantage of the proposed experimental set-up using *ex-vivo* skin as readout. Although an *ex-vivo* rabbit ear mimics the human skin very well, it has a limited storage time and histological evaluation using skin samples is tedious and time consuming. In this perspective, the development of multilayered synthetic epidermal skin equivalents is looking promising, also because automated roughness measurements can be used instead of histological analyses as read-out of the surface damage.<sup>16</sup>

The correlation study showed that under comparable loading conditions the stratum corneum thickness is significantly reduced when tested on dry artificial turf in contrast to a wet surface condition or dry natural grass. This implicates the degree of skin damage is not only related to the level of stress but also to the characteristics of the counter surface. From an engineering point of view, skin abrasion injuries are a result of a wear process, and wear is typically defined as the loss of material from a surface by the contact and relative motion with a solid, liquid or gaseous counter body.<sup>17,18</sup> One of the wear mechanisms of interest is classified as abrasive wear and occurs when a solid object is in sliding contact with a harder rough counter material. In general, abrasive wear results from scratching and/or micro-cutting. Although hardness and/or roughness are not considered in this study, the observed differences in tolerance of the skin between artificial turf and natural grass can probably be explained by these wear parameters. This means that tribological investigations on component level of yarns and infill can contribute to a better knowledge of the skin-turf friction when surface roughness and possibly the hardness are also taken into account.<sup>19,20</sup>

Unfortunately, current research in the field of skin-friendly artificial turf surfaces is concentrated on friction coefficient measurements. It is assumed that the level of friction

is correlated to the skin abrasion.<sup>7,21,22</sup> However, there is no simple correlation between friction and skin damage (wear). In a qualitative way it seems reasonable to expect relatively more skin damage in case of high frictional forces but it is quite possible for material combinations to produce very similar frictional forces but very different wear behaviour.<sup>23</sup> Sanchis et al. showed that the correlation between the coefficient of friction and damage when using a silicone rubber skin replacer was not good. When tested on different artificial turf surfaces similar coefficients of friction resulted in different roughness values of the worn rubber.<sup>7</sup> It was suggested that other mechanisms than friction are responsible for the observed damage.

In the interaction between skin and artificial turf a number of phenomena occur simultaneously, both on a macroscopic and a more localised microscopic scale.<sup>24</sup> These mechanisms include adhesion between the two surfaces, lubrication, deformation of the skin, the fibres as well as the infill material and micro-ploughing and scratching. The combination of these mechanisms results in friction in the contact as well as in damage to the skin. Whilst that means that both the experienced friction and the resulting skin damage both originate from these basic mechanisms, there is no causal relationship between the level of friction in the contact and the damage to the skin and no obvious quantitative correlation exists.

In conclusion, this study provides unique biomechanical data of the load tolerance of skin to impact on dry and wet artificial turf and natural grass. The developed insights are valuable for manufacturers of artificial turf in defining the design space. Additionally, it helps governing bodies in setting standards regarding the sliding friendliness of artificial turf.

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## Supplementary information

The vertical reaction force ( $F_z$ ) is calculated by the following equation

$$F_z = \alpha_1 a_1 M_1 + \alpha_2 a_2 M_2 \quad [\text{N}] \quad (1)$$

Where:

$\alpha_1$  = calibration constant of the vertical accelerometer of the upper mass [-]

$a_1$  = vertical acceleration of upper mass [ $\text{m s}^{-2}$ ]

$M_1$  = upper mass [kg]

$\alpha_2$  = calibration constant of the vertical accelerometer of the lower mass [-]

$a_2$  = vertical acceleration of lower mass [ $\text{m s}^{-2}$ ]

$M_2$  = lower mass [kg]

The horizontal reaction force ( $F_y$ ) is given by

$$F_y = \alpha_3 a_3 (M_1 + M_2) \quad [\text{N}] \quad (2)$$

Where:

$\alpha_3$  = calibration constant of the horizontal accelerometer of the impact body [-]

$a_3$  = horizontal acceleration of the impact body [ $\text{m s}^{-2}$ ]

$M_1$  = upper mass [kg]

$M_2$  = lower mass [kg]

The calibration constants were calculated from a free fall test given the following equation

$$\alpha_1 a_1 = \alpha_2 a_2 = \alpha_3 a_3 = G \quad [\text{m s}^{-2}] \quad (3)$$

Where:

$\alpha_1$  = calibration constant of the vertical accelerometer of the upper mass [-]

$a_1$  = vertical acceleration of upper mass [ $\text{m s}^{-2}$ ]

$\alpha_2$  = calibration constant of the vertical accelerometer of the lower mass [-]

$a_2$  = vertical acceleration of lower mass [ $\text{m s}^{-2}$ ]

$\alpha_3$  = calibration constant of the horizontal accelerometer of the impact body [-]

$a_3$  = horizontal acceleration of the impact body [ $\text{m s}^{-2}$ ]

$G$  = gravitational constant [ $\text{m s}^{-2}$ ]

The corresponding normal ( $\sigma_z$ ) and shear stress ( $\tau_y$ ) are defined as:

$$\sigma_z = F_z / A_s \quad [\text{N cm}^{-2}] \quad (4)$$

and

$$\tau_y = F_y / A_s \quad [\text{N cm}^{-2}] \quad (5)$$

Where:

$$A_s = \text{the contact area of the skin sample} \quad [\text{cm}^2] \quad (6)$$

In wear analyses often the Archard wear equation is applied which asserts that the wear volume is directly proportional to the product of the normal load and the horizontal sliding distance. Therefore, the work related term during impact ( $W$ ) is calculated with the aid of the following formula:

$$W = \int_0^{s_{\max}} F_z ds \quad [\text{Nm}] \quad (7)$$

Where

$s$  = instantaneous horizontal displacement during impact [m]

$s_{\max}$  = maximum horizontal displacement during impact [m]

Finally, the kinetic energy ( $E_{\text{kin}}$ ) before impact is derived using to the following equation

$$E_{\text{kin}} = \frac{1}{2} (M_1 + M_2) (v_z^2 + v_y^2) \quad [\text{Nm}] \quad (8)$$

Where

$v_z$  = vertical velocity component before impact [ $\text{m}\cdot\text{s}^{-2}$ ]

$v_y$  = horizontal velocity component before impact [ $\text{m}\cdot\text{s}^{-2}$ ]

$M_1$  = upper mass [kg]

$M_2$  = lower mass [kg]





# 4

## Summary and general discussion



## Summary

With its ingenious multi-layered structure, the skin is able to provide adequate resistance to e.g. mechanical, chemical and thermal load. Although the human skin is flexible and has a huge capability to absorb mechanical load, it has limitations resulting in failure or breakdown. In **Chapter 1** is described that the introduction of artificial turf into soccer is strongly associated with acute skin injury due to player-surface contact. Current standards to assess artificial turf pitches are under consideration because they do not simulate realistic loads of a sliding.<sup>1,2</sup> More in general, fundamental insight into the acute skin injury mechanism, contributing to the development of adequate preventive measures, is missing at the moment. The overall aim of this thesis was to gain understanding in the acute skin injury mechanism of player-surface contact on artificial turf by studying the injury extent and skin injury mechanism.

The first step towards injury prevention is establishing the extent of the injury problem. Therefore, knowledge of the incidence and severity of sliding induced skin injuries on artificial turf pitches need to be inventoried. **Chapter 2** covers the survey in using the players' skin as readout by applying both invasive and novel non-invasive techniques in assessing and quantifying the injury extent.

As presented in **Chapter 2.1** common injury reporting methods are mainly based on time lost from participation or the need for medical attention.<sup>3</sup> Because skin abrasions seldomly lead to absence or medical attention, they are often not reported.<sup>4</sup> When reported, the incidence of abrasion injuries, varies from 0.8 to 6.1 injuries per 1000 players-hours.<sup>5,6,7</sup> Based on our literature study the following extrinsic risk factors have a positive effect on preventing abrasion type of injuries namely the use of protective equipment, a skin lubricant and a wet surface condition.<sup>8,9</sup> Conflicting results regarding the intrinsic risk factors age and gender were found. More important, essential biomechanical data of the sliding event is currently lacking. According to Meeuwisse the event itself is the main risk factor in acute injuries.<sup>10</sup> External and/or internal risk factors contribute to a lesser extent to the cause of injury.

A newly developed and validated psychometric instrument is presented in **Chapter 2.2**. It measures the surface performance based on the players' perceptions. With the aid of the Football Turf Performance Questionnaire (FTPQ) we were able to compare pitches and to identify predictors for overall performance and sliding friendliness. Multiple regression analysis revealed that the descriptors "burning feeling of the skin after a sliding movement" and indicators "skin irritation" and "traction" are the best predictors for sliding friendliness. Principle Component Analysis showed a strong correlation between the factor "skin discomfort" and skin injury descriptors "redness of the skin" and "abrasion". This implies that a skin injury assessment technique can be useful as a readout for sliding discomfort.

So far it has been unclear what the clinical and immunohistological effects of a sliding on artificial turf are. In **Chapter 2.3** we reported the clinical and immunohistological results of an invasive study of sliding induced skin lesions. Clinically, a sliding performed on artificial turf caused less erythema but more abrasion compared to dry natural grass. At a histological level artificial turf and dry natural grass compared to wet natural grass disrupted the stratum corneum the most, resulting in a reduced barrier function.<sup>11,12</sup>

The results of the invasive study showed the potential of the skin as a readout system for skin damage. Although valuable, invasive methods are not applicable on a larger scale. For this reason novel non-invasive methods to assess the skin damage are needed. The development of a non-invasive method based on a psychosensorial assessment is presented in **Chapter 2.4**. In analogy with, the Psoriasis Area and Severity Index (PASI) which measures the severity of Psoriatic lesions, the proposed Skin Damage Area and Severity Index (SDASI) scores sliding induced skin lesions.<sup>13</sup> Correlation analyses revealed that the SDASI correlates strongly both with the perceived skin irritation and sliding friendliness by players. Due to the easiness of use, the SDASI could be of interest for injury surveillance studies to obtain insight in the extent of skin injuries of current artificial turf pitches worldwide. The SDASI, typically is related to clinical superficial parameters but does not provide information of the deeper cellular response.

Understanding the injury mechanism is the next step of the injury prevention model described by van Mechelen et al.<sup>14</sup> In **Chapter 3** we discuss the findings of our exploratory survey into the biomechanical load and load tolerance of the skin during the landing phase of a sliding.

Firstly, morphology data of damaged skin obtained with an *in-vivo* non-invasive model based on tape stripping and Reflectance Confocal Microscopy (RCM) are reported in **Chapter 3.1**. RCM imaging and histology results are compared to tape stripped skin. A strong correlation between epidermal thickness measurements was found. Besides epidermal thickness also keratinocyte proliferation and parakeratosis are parameters that can be studied in time by RCM. Complementary to a clinical assessment, RCM can easily be applied in larger studies and provide insight in the biological response of sliding induced injuries over time. Further, a resemblance between the histology of acute and repeated 10x or 15x tape stripped skin and sliding induced skin injuries was demonstrated. This implies that tape stripping can be useful as skin damage model.

In analogy with reported peak loads during fall studies we hypothesize that peak loads on the skin during the landing phase are important for inducing acute skin injuries.<sup>15,16</sup> **Chapter 3.2** provides us biomechanical data from video analysis and load measurements, using an in-ground force plate, of the impact phase of a sliding tackle. Depending on the sliding technique, the vertical peak forces are in the range of 3 to 6.5 times the body weight. This is in accordance with reported data from fall studies.<sup>17</sup> In combination with the observed skin lesion, obtained from the SDASI assessment, a combined normal-shear stress of at least 24 and 14 Ncm<sup>-2</sup> induces abrasion injuries on dry artificial turf. The findings

confirm that high peak stresses during the landing phase of a sliding are critical for inducing skin injuries on the knee and thigh. In literature, scarcely reference data of critical skin failure stress is found. Only from repetitive *in-vivo* mechanical combined stress experiments we learn that skin breakdown occurs earlier when shear stress increases.<sup>18</sup> Reducing these horizontal peak stresses, for example, by decreasing the friction could be of interest in reducing abrasion type of skin injuries.

Since skin failure data under combined impact load conditions are lacking, we report in **Chapter 3.3** about the development of a biaxial load applicator. In combination with an *ex-vivo* rabbit ear model the load tolerance of skin to impact on dry and wet artificial turf and dry natural grass was investigated. It was found that, in contrast to natural grass, skin damage on dry artificial turf is strongly related to the magnitude of the impact load. Wetting of the artificial turf system improves the load tolerance of skin to impact. This study showed that the degree of skin damage is not only related to the level of stresses but also to the characteristics of the counter surface. Obviously, there is no causal relationship between the level of friction in the contact area and the damage to the skin.

## General discussion

Material-skin contact is a relatively novel research topic with applications in the field of clothing, footwear, airbags, hand tools and prosthesis. The aim is to improve the comfort or at least reduce the discomfort of the user. Most published work is limited to either *in-vivo* friction experiments at low forces and velocity or perceptive studies. The possible effects and changes of the skin due to the contact are not often studied. One can state that the research domain is currently dominated by mechanical and material engineers. Until now, the added value of dermatology and their specific expertise of both clinical response and deeper histological effects has not been explored. This thesis aimed to build a bridge between dermatology and engineering by using the skin as readout system to study the extent and the injury mechanism of sliding induced skin injuries on artificial turf.

Measuring the players' perception is an obvious method to assess sport surfaces and provides useful information for both designers and sport governing organisation. Although players' perception studies are presented in literature regularly, there is no general consensus on how to assess the players' perception regarding the different performance characteristics. The Football Turf Performance Questionnaire (FTPQ), which is based on the performance characteristics summarised in the FIFA handbook, is an attempt to develop a psychometric instrument to assess artificial turf pitches systematically. As for all subject studies, the sample size, subject selection and other possible influencing factors such as environmental conditions and user instructions have to be taken into account. A consensus statement regarding the conductance of user trails initiated by

scientific institutes and supported by sport governing bodies will contribute to standardisation and improvement of the quality of user assessments.

In order to gain insight into the extent of sliding induced skin injuries we conducted both invasive and non-invasive studies. An invasive method is not applicable for large cohort studies. However, these invasive studies provided insight in the biological response of skin tissue and skin morphology. The introduced non-invasive assessment technique, Skin Damage Area and Severity Index (SDASI), is suitable to apply in larger studies. In combination with a mobile application, data collection can easily be performed. It must be mentioned that the SDASI scoring system is developed based on skin types I, II and III according to the Fitzpatrick Skin type classification.<sup>19</sup> The applicability for darker skin types should be investigated in future.

Although the FTPQ and SDASI methods are useful instruments to assess the sliding friendliness of artificial turf pitches, there is a strong belief among sport governing bodies in instrumental measurements. In order to develop an apparatus to assess the sliding friendliness, knowledge regarding the injury mechanism is essential. At the moment there are three main skin injury mechanisms reported in relation to player-surface contact which are either related to friction, abrasion or thermal heat. The current standardized measurement methods use either the friction coefficient, weight loss or temperature rise as readout. At the moment it is unclear how the existing standardised methods correlate with the players' perception. For future research it is recommended to set up a correlation study using the developed FTPQ and SDASI to evaluate the effectiveness of the current instrumental measurements in discriminating between sliding friendly and sliding unfriendly pitches.

Our exploratory biomechanical experiments provided preliminary load data and essential new insight in the sliding event which induces a skin injury. It revealed a clear relation between the injury location, area of contact during the impact phase and peak loads. This led to the assumption that the impact phase is more critical in inducing skin injuries than the gliding phase. These new insights and the need for an instrumental method led to the development of a novel apparatus: the biaxial load applicator. With the introduction of the biaxial load applicator it is now possible to systematically investigate the load tolerance of skin due to impact on any type of sport surface. Within our study only one type of artificial turf system is used. In reality a large variety of turf configurations exist. Investigating the contribution of the individual system components on the abrasiveness to the skin is relevant. It must be emphasized that although the impact loads are high, only epidermal damage was noticed. This implies that the abrasive effect occurs on a micro level rather than on a macro level. What really happens in the area of contact on a submicron level is not yet understood and is subject of future research.

The use of an *ex-vivo* skin model showed to be successful. However, such a model is not desirable for ethical reasons and tedious analyses. Therefore it would be interesting to specify and develop a suitable and reproducible skin replacer material. Ideally, the

abrasion characteristics of the skin substitute is correlated to normal skin under the specified load conditions during impact. Finally, our *ex-vivo* skin model can be used as benchmark to evaluate the abrasive behaviour of the skin substitute under defined loading conditions.

With more than 1500 installed artificial soccer pitches and over 1.2 million active soccer players in the Netherlands the social relevance of skin injury prevention research is obvious. On the other hand it is difficult to build a business case because data of related medical health care costs are currently lacking. Setting minimum standards for sliding friendliness by sport governing bodies will not only improve the pleasance of playing but will also reduce related health care costs. In addition it will create business opportunities for innovative sliding friendly concepts.

Even when the health care related costs of sliding induced skin injuries are low, prevention research is still desirable from a social-welfare perspective. As stated as one of the principles of the constitution of the World Health Organisation, health is not merely the absence of disease or infirmity but is a state of complete physical, mental and social well-being.<sup>20</sup>

Finally, from a dermatological perspective this thesis provided techniques to gain insight in to the pathophysiology of wounds which is relevant for studying wound recovery and healing. The SDASI technique for example can be applied as alternative wound assessment technique in a clinical setting where quantitative methods are essential for checking the response to treatment for example decubitus or diabetes related wound.

This survey did not focus on the development of new artificial turf systems or new safety standards to access artificial turf systems. As this is the work and responsibility of manufacturers and governing sport bodies, respectively. In this thesis it was aimed to achieve a broader insight into the injury mechanism of sliding induced skin injuries by using the skin as a readout system. It provided innovative non-invasive tools, which manufacturers and governing bodies can use to evaluate their novel products or developing new standards regarding sliding friendliness in the near future.

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# 5

## Nederlandse samenvatting



## Samenvatting

Door de ingenieuze multi-gelaagde structuur is de huid in staat weerstand te bieden aan mechanische, chemische en thermische belastingen. De menselijke huid is flexibel en in zekere mate belastbaar, maar boven bepaalde belastbaarheidsgrenzen kan het leiden tot huidschade. In **hoofdstuk 1** is beschreven dat, sinds de introductie in het voetbal, kunstgras sterk wordt geassocieerd met acute huidschade ten gevolge van speler-veld contact. Huidige normen om kunstgrassystemen te beoordelen op slidingvriendelijkheid staan ter discussie omdat de testcondities en belastingen niet de slidingbeweging realistisch nabootsen. Op dit moment ontbreekt het inzicht in het fundamentele mechanisme van het ontstaan van huidschade tijdens een slidingbeweging. Dit inzicht is belangrijk voor de ontwikkeling van preventieve maatregelen. Het doel van het onderzoek was inzicht te krijgen in de omvang en ernst van acute huidschade op kunstgras ten gevolge van speler-veld contact en het huidschade-mechanisme zelf.

Het vaststellen van de omvang en ernst van een blessure is de eerste stap ter voorkoming van blessures. Informatie over de incidentie van huidschade ten gevolge van een slidingbeweging moet daarom eerst in kaart worden gebracht. **Hoofdstuk 2** behandelt de bevindingen van ons onderzoek waarbij de speler als uitlezing is gebruikt. Zowel invasieve als nieuwe niet-invasieve technieken zijn toegepast om de ernst en omvang van huidschade te kwantificeren.

**Hoofdstuk 2.1** beschrijft dat bestaande blessureregistratie methoden voornamelijk gebaseerd zijn op tijdverlies als gevolg van uitval van de speler of de noodzaak van medische verzorging. Huidblessures worden vaak niet gerapporteerd omdat ze zelden leiden tot het missen van trainingen of wedstrijden. Daarnaast behoeven deze blessures zelden medische aandacht. Op basis van blessuredata uit de literatuur blijkt dat de incidentie van abrasieve huidschade varieert tussen 0.8 en 6.1 huidverwondingen per 1000 speeluren. Op basis van het uitgevoerde literatuuronderzoek blijkt tevens dat de volgende extrinsieke risicofactoren: het gebruik van beschermende kleding, een smeermiddel op de huid en een nat speelveld een positief effect hebben op het voorkomen van abrasieve huidschade. Ten aanzien van de intrinsieke risicofactoren leeftijd en geslacht werd tegenstrijdige informatie gevonden.

Volgens Meeuwisse is de gebeurtenis, in ons geval de slidingbeweging, de belangrijkste risicofactor voor het ontstaan van acute huidschade. Externe en/of interne risicofactoren dragen in mindere mate bij aan het ontstaan van een blessure. Essentiële biomechanische data over de slidingbeweging zijn echter op dit moment niet voorhanden.

Een nieuw ontwikkeld en gevalideerd psychometrisch meetinstrument, de zogenaamde *Football Turf Performance Questionnaire* (FTPQ), wordt geïntroduceerd in **hoofdstuk 2.2**. Het meet de veldprestaties op basis van waarnemingen van de spelers. Met hulp van de FTPQ zijn voorspellers bepaald voor de algehele prestatie van een kunstgrasveld en meer specifiek de slidingvriendelijkheid. Uit regressieanalyse is gebleken dat het belevings-

kenmerk "het brandende gevoel van de huid na een slidingbeweging" en de prestatie indicatoren "huidirritatie" en "tractie" de beste voorspellers zijn voor de beleving van slidingvriendelijkheid. Uit de Principale componentenanalyse (PCA) bleek een sterke correlatie tussen de factor "huid discomfort" en de klinische huidschade kenmerken "roodheid van de huid" en "abrasie". Dit houdt in dat een huidschade beoordelingsmethodiek gebruikt zou kunnen worden om de mate van slidingvriendelijkheid van een veld te kwantificeren.

Het is tot dusver onduidelijk wat de klinische en immunohistologische gevolgen van een sliding op kunstgras zijn. In **hoofdstuk 2.3** worden daarom de resultaten besproken van een invasieve studie naar de klinische en immunohistologische gevolgen van een slidingbeweging. Klinisch gezien veroorzaakt een sliding op droog kunstgras minder erythema maar meer abrasie in vergelijking tot droog natuurgras. Op cellulair niveau wordt het stratum corneum op droog natuurgras en droog kunstgras op een vergelijkbare wijze beschadigd wat resulteert in een verminderde barrièrefunctie. Opvallend is dat een sliding op nat natuurgras niet resulteert in beschadiging van het stratum corneum.

De resultaten van de invasieve studie tonen het belang aan om de huid als uitlees-systeem voor huidschade te gebruiken. Invasieve methoden zijn echter niet toepasbaar op grote schaal. Om deze reden zijn niet-invasieve methoden nodig om huidschade te kunnen beoordelen. De ontwikkeling van een nieuwe niet-invasieve methode op basis van een psychosensorische evaluatie wordt behandeld in **hoofdstuk 2.4**. In analogie met de *Psoriasis Area and Severity Index* (PASI), welke de ernst van een psoriasis laesie scoort, scoort de voorgestelde *Skin Damage Area and Severity Index* (SDASI) de huidschade ten gevolge van een sliding. Uit correlatie analyse bleek dat de SDASI sterk correleert met de spelersbeleving van huidirritatie en slidingvriendelijkheid. Vanwege de eenvoud en het gebruiksgemak zou de SDASI van toegevoegde waarde kunnen zijn bij blessureregistratie-studies. Opgemerkt dient te worden dat de SDASI is gebaseerd op klinische parameters en geen informatie verschaft over de diepere cellulaire respons.

Inzicht in het huidschade-mechanisme is de volgende stap van het blessure preventiemodel zoals beschreven door Van Mechelen. In **hoofdstuk 3** bespreken we de bevindingen van ons verkennend onderzoek naar de biomechanische belasting en de belastbaarheid van de huid tijdens de impactfase van een slidingbeweging.

De morfologie van beschadigde huid is beschreven in **hoofdstuk 3.1**. Dit werd bestudeerd aan de hand van een niet-invasief in-vivo model waarbij de huid wordt gestipt door middel van tape (tape strippen). De morfologische veranderingen werden bekeken door gebruik te maken van Reflectie Confocale Microscopie (RCM). RCM beelden en histologisch onderzoek van getapestripte huid werden met elkaar vergeleken. Tussen RCM metingen en metingen in de histologische coupes werd een sterke correlatie gevonden tussen epidermale diktemetingen. Daarnaast konden met RCM proliferatie en parakeratose worden waargenomen en in de tijd worden bestudeerd. In aanvulling op klinisch onderzoek kan RCM op grotere schaal worden ingezet om de biologische response in de huid ten gevolge van het huid-veld contact in de tijd te bestuderen. Uit

histologisch onderzoek blijkt verder dat er een sterke overeenkomst bestaat tussen acute en herhaald (10x of 15x) tapegestripte huid en huidschade ten gevolge van huid-veld contact. Dit impliceert dat tapestrippen een zinvol model is om huidschade te bestuderen.

In analogie met de in valstudies gepubliceerde piekbelastingen veronderstellen we dat piekbelastingen op de huid tijdens de landingsfase van een sliding belangrijk zijn voor het induceren van acute huidschade. **Hoofdstuk 3.2** beschrijft de bevindingen van de biomechanische analyse van een slidingbeweging. Aan de hand van video analyse en belastingmetingen met een krachtenplatform werd de landingsfase bestudeerd. De gemeten verticale piekkracht varieert tussen de 3 en 6,5 maal het lichaamsgewicht en is sterk afhankelijk van de slidingtechniek. Aan de hand van de waargenomen huidschade is vervolgens afgeleid dat een gecombineerde normaal- en afschuifspanning van tenminste de 24 en 14 Ncm<sup>2</sup> voldoende is om huidschade te veroorzaken op droog kunstgras. De bevindingen bevestigen dat een hoge piekspanning tijdens de landingsfase van een sliding cruciaal is voor het induceren van huidschade op de knie en het bovenbeen. In de literatuur is nauwelijks data te vinden over de kritische spanning waarop huidschade optreedt. Alleen van in-vivo metingen onder wisselende gecombineerde belasting leren we dat huidschade eerder optreedt als de schuifspanningscomponent wordt verhoogd. Het verminderen van de afschuifspanning door middel van het verlagen van de wrijving kan van belang zijn voor het verminderen van het risico op huidschade tijdens een slidingbeweging.

Aangezien belastbaarheidsdata van de huid onder gecombineerde belastingscondities ontbreken gaan we tenslotte in **hoofdstuk 3.3** in op de ontwikkeling een biaxiaal belastingsapparaat welke de impactbelasting op een kunstgrassysteem nabootst. In combinatie met een *ex-vivo* konijnenoormodel kan de belastbaarheid van de huid onder verschillende impactcondities op droog en nat kunstgras en droog natuurgras systematisch worden onderzocht. In tegenstelling tot droog natuurgras is de huidschade op droog kunstgras sterk gerelateerd aan de grootte van de belasting. Bevochtiging van het kunstgras verbetert de belastbaarheid van de huid en reduceert huidschade. Deze studie toonde tevens aan dat de mate van huidschade niet alleen is gerelateerd aan de grootte van de belasting maar ook aan de veldeigenschappen. Blijkbaar bestaat er dus geen causaal verband tussen wrijving en huidschade.

Het onderzoeksveld van huid-materiaal contact wordt op dit moment gedomineerd door fysici en ergonomen. Door de huid als uitleessysteem te gebruiken kan dermatologie, met haar kennis en kunde, van toegevoegde waarde zijn voor dit onderzoeksveld. De ontwikkelde kennis en inzichten van ons onderzoek zijn zowel van belang voor producenten, keuringsinstanties als sportbonden. Producenten kunnen aan de hand van de ontwikkelde methoden nieuwe concepten ontwikkelen en beoordelen. Sportbonden en keuringsinstanties kunnen op basis van de nieuwe inzichten een slidingsvriendelijkheidsnorm ontwikkelen voor kunstgrassystemen met als doel om de veiligheid op dit aspect te borgen en speelplezier voor de speler te verhogen.



# 6

List of publications

Curriculum Vitae

Dankwoord

List of abbreviations

List of symbols



## List of publications

### Publications related to this thesis

- Peppelman, M, van den Eijnde WAJ, Langewouters AM, Weghuis MO, van Erp PE.  
The potential of the skin as a readout system to test artificial turf systems: clinical and immunohistological effects of a sliding on natural grass and artificial turf. *Int J Sports Med* 2013;34(9): 783-788. Epub 2013/02/28
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- van de Eijnde WAJ, Masen M, Lamers E, van de Kerkhof PCM, Peppelman M, van Erp PE. The load tolerance of skin during impact on artificial turf using ex-vivo skin as the readout system. *Submitted*.

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- Schols, EH, van den Eijnde WAJ, Heus R. A method for assessing thermal comfort of shoes using a "sweating" foot. *Eur J Appl Physiol* 2004; 92(6): 706-709; Epub 2004/09/01
- Jurgens, E, van den Eijnde WAJ. Sometimes a shoe is just a shoe? Not in the workplace; Optimale veiligheidsschoenen voorkomen klachten en arbeidsverzuim. *TBV – Tijdschrift voor Bedrijfs- en Verzekeringsgeneeskunde*. 2013; 21(1) (NL) Epub 2013/01/01



## Curriculum Vitae

Wilbert van den Eijnde werd geboren op 14 september 1968 te Beek en Donk. Na het behalen van zijn VWO diploma aan het Marcopedius College in Gemert begon hij in 1987 aan zijn studie Werktuigbouwkunde aan de Technische Hogeschool in Venlo. Zijn afstudeeropdracht aan de Technische Universiteit Eindhoven over “het beschrijven van uitbuiking tijdens stuiken, middels de bovengrensanalyse” werd door het college van Rijksgecommiteerden bekroond met de Prof. Niestenprijs 1991.

Na zijn militaire dienstplicht begon Wilbert in 1992 zijn loopbaan als research assistent in de mechanische onderzoeksgroep op het Philips Natuurkundig Laboratorium.

In 1998 maakte Wilbert de overstap naar TNO Industrie. Als projectleider ‘Leer en Schoenen’ was hij verantwoordelijk voor het in opdracht opstellen, doorvoeren en rapporteren van producttesten op basis van gestandaardiseerde normen of eigen ontwikkelde protocollen. Gaande weg kwam steeds meer de aandacht te liggen op de eindgebruiker. Met als gevolg dat in 2001 de activiteiten werden ondergebracht in de afdeling Mensgericht Productonderzoek bij TNO Industrie en Techniek in Eindhoven. Naast het werkveld van schoeisel werden in 2003 de werkzaamheden uitgebreid naar ontharingsproducten. Middels gebruikersonderzoek werden in opdracht de prestaties van ontharingsproducten onderzocht. In dezelfde periode ontstond het eerste contact met dr. Piet van Erp, wetenschappelijk onderzoeker op de afdeling Dermatologie van het Radboud Universitair Medisch Centrum Nijmegen (Radboudumc). In samenwerking met dr. Piet van Erp werden diverse exploratieve klinische en cytometrische studies opgezet en uitgevoerd naar effecten van ontharen.

In 2007 richtte Wilbert samen met TNO Bedrijven de start-up ConsumersVoice op welke zich volledig richt op consumenten- en gebruikersonderzoek met als doel de slagingskans van innovatietrajecten voor klanten te vergroten. De samenwerking met TenCate en het Radboudumc heeft in 2010 geleid tot de ontwikkeling van een kennisontwikkelingsproject met Philips Drachten, Reden, Universiteit Twente, ISA Sport, Universiteit Wageningen, Descol en Deltec genaamd New Business by Enhanced Skin Comfort. De resultaten die in het kader van dit onderzoek zijn verkregen zijn samengevat in verschillende wetenschappelijke publicaties en in dit proefschrift. In diverse nationale en internationale bijeenkomsten heeft Wilbert de verkregen onderzoeksresultaten gepresenteerd.

Naast ConsumersVoice heeft Wilbert met zakenpartner Frank Gervedink-Nijhuis in 2015 TwinX-Noord opgericht. TwinX-Noord, acroniem voor Together we innovate, richt zich specifiek op het ontwikkelen, managen en begeleiding van innovatieprojecten in Noord- en Oost-Nederland. In dit verband is in november 2015 in samenwerking met de Noordelijke Ontwikkelingsmaatschappij (NOM) en 34 regionale partners, waaronder Philips Drachten, het innovatieproject Region of Smart Factories (RoSF) ontwikkeld en van start gegaan.



## Dankwoord

Een leven lang leren! Dat was het eerste wat in mij op kwam toen ik begon aan mijn dankwoord.

Alhoewel van overheidswege gepropageerd, is het vooral iets wat vanuit jezelf moet komen. Een attitude. Kritisch en met open vizier op zoek gaan naar antwoorden. Het experiment aan willen gaan, mensen ontmoeten. Vallen en weer opstaan. Kortom, net als het leven zelf. Elke dag heeft immers een component van een leven lang leren in zich.

Ik ben dankbaar voor alle ontmoetingen, kansen, geslaagde en minder geslaagde experimenten die ik in de afgelopen jaren in samenwerking met anderen heb mogen meemaken en beleven.

In het kader van dit onderzoek wil ik een aantal mensen in het bijzonder bedanken.

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*Dr. Piet van Erp.* Al sinds onze eerste ontmoeting was er een bijzondere klik waarbij we telkens het experiment zijn aangegaan. Welke uiteindelijk heeft geleid tot het voorliggende proefschrift. Alleen jij had dit kunnen vermoeden. Je hebt me geïntroduceerd in de wondere wereld van de "levende huid". Je bezit de gave om bruggen te slaan en bent een geweldig mensen-mens waarbij altijd de deur opstaat. Ik had me geen betere mentor, collega en vriend kunnen voorstellen. Een geruststellende gedachte is dat we nog lang niet klaar zijn met experimenteren!

*Dr. Malou Peppelman.* Een rots in de branding. De focus in combinatie met je enthousiasme is met geen pen te beschrijven. Zonder jou inbreng was het proefschrift minstens 2x zo dik geworden, zouden presentaties 3x zolang hebben geduurd en was ik op dit moment nog lang niet klaar geweest. Het was een voorrecht om met je samen te werken. Ik had me naast Piet geen betere copromotor kunnen wensen.

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*Ir. Martin Oldeweghuis.* Als geestelijk vader van het kunstgras- en spelersonderzoek binnen TenCate ben jij instaat om mensen op een ongekende manier te enthousiasmeren. Binnen het landschap van business developers ben je one-of-a-kind. Met jou in de buurt is er in Nijverdal en omstreken daadwerkelijk altijd wel wat te doen! Als voorzitter van Stichting Sport en Leisure wil ik je bedanken voor je steun en het vertrouwen die je Frank en mij de

afgelopen jaren hebt gegeven. Ik hoop dat onze samenwerking nog lang mag duren. De BBQ in Friesland heb je nog tegoe!

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*Prof Dr. Emile van der Heide.* Binnen TNO had ik al het genoeg om met je samen te werken. Samen met Ronald Heus hadden we ons eerste onderzoeksproject geïnitieerd binnen het relatieve nieuwe werkveld van huidtribologie. Het is mooi om te zien hoe we deze draad met het huidige project hebben kunnen voortzetten. Tevens wil ik je bedanken voor deelname aan de manuscript commissie. Ik hoop dat er nog meerdere vormen van samenwerking volgen.

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*Ir. Frank Gervedink-Nijhuis.* Lotgenoot, partner-in-crime. Als duo Jut en Jul hebben we de afgelopen jaren veel lief en leed met elkaar gedeeld. Welk etiketje je ook maar op onze samenwerking probeer te plakken er is maar een labeltje wat alles dekt: Vriendschap! Je bent ongekend getalenteerd. Het is een waar genoeg om met je samen te werken. Ik kan niet wachten om samen met jou nieuwe experimenten aan te gaan.

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*Elke dag het experiment aangegaan,  
elke dag voor ons klaar gestaan.  
Nu eindelijk rust gevonden,  
maar voor altijd met ons hart verbonden.*

***Wilbert***



## List of abbreviations

A	Abrasion
ANOVA	Analyses of variance
ASTM	American Society for Testing and Materials
Beta	Unstandardized regression coefficients
BMI	Body Mass Index
CD3	Cluster of differentiation 3
DAB	Diaminobenzidine
E	Erythema
EDTA	Ethylenediaminetetraacetic acid
EPDM	Ethylene Propylene Diene Monomer
FIFA	Fédération Internationale de Football
F	Variance Ratio
F-MARC	Fédération Internationale de Football Association Medical Assessment and Research Centre
FTPD	Football Turf Performance Descriptors
FTPI	Football Turf Performance Indicators
FTPQ	Football Turf Performance Questionnaire
hBD-2	Human beta defensin-2
HE	Hematoxylin-eosin
HSP70	Heat shock protein 70
IFAB	International Football Association Board
IHC	Immunohistochemical
K16	Cytokeratin 16
K10	Cytokeratin 10
Ki67	Protein associated with cellular proliferation
KNVB	Koninklijke Nederlandse Voetbalbond
LSR	Low Sliding Resistance
MRSA	Methicillin-Resistant Staphylococcus Aureus
N	Normal scoring
n	Number of subjects or samples
p	Probability
PA	Polyamide (Nylon)
PASI	Psoriasis Area and Severity Index
PBS	Phosphate Buffered Saline
PCA	Principal Component Analysis
PE	Polyethylene
PMN	Polymorphonuclear
PP	Polypropylene
r	Pearson correlation coefficient
R	Correlation coefficient regression analysis
R <sup>2</sup>	Coefficient of determination regression analysis
RCM	Reflectance confocal microscopy

SBR	Styrene-Butadiene-Rubber
SC	Stratum corneum
SD	Standard Devication
SDASI	Skin Damage Area and Severity Index
TE	Type of exudation
TWEL	Transepidermal water loss
TPE	Thermoplastic Elastomers
TPE-2	Thermoplastic Elastomers (alternative)
UEFA	Union of European Football Associations
X	Out of plane
Y	Horizontal direction
Z	Vertical direction

## List of symbols

$A_s$	area of the skin lesion	[cm <sup>2</sup> ]
$A_{s,f}$	relative involved area of the skin lesion	
$a_1$	vertical acceleration of upper mass	[ms <sup>-2</sup> ]
$a_2$	vertical acceleration of lower mass	[ms <sup>-2</sup> ]
$a_3$	horizontal acceleration of the impact body	[ms <sup>-2</sup> ]
$E_{kin}$	kinetic energy	[Nm]
$F_{tot}$	total force of impact force.	[N]
$\vec{F}$	instantaneous ground reaction force during impact in Newton	[N]
$F_z$	vertical component of impact force	[N]
$F_x$	horizontal out-of-plane component of impact force	[N]
$F_y$	horizontal component of impact force	[N]
$G$	gravitational constant	[ms <sup>-2</sup> ]
$M_1$	upper mass	[kg]
$M_2$	lower mass	[kg]
$s$	instantaneous horizontal displacement during impact	[m]
$s_{max}$	maximum horizontal displacement during impact	[m]
$t_i$	initial time of impact, defined as the time when the ground reaction force first exceeds the participant's body weight	[s]
$t_f$	final time of impact, defined as the first time when the ground reaction force is lower than the participant's body weight after the impact of the hip	[s]
$\Delta t$	time interval of impact	[s]
$v_i$	average horizontal initial speed before impact	[ms <sup>-1</sup> ]
$v_z$	vertical velocity component before impact	[ms <sup>-1</sup> ]
$v_y$	horizontal velocity component before impact	[ms <sup>-1</sup> ]
$W$	work related term during impact	[Nm]
$\alpha_1$	calibration constant of the vertical accelerometer of the upper mass	[-]
$\alpha_2$	calibration constant of the vertical accelerometer of the lower mass	[-]
$\alpha_3$	calibration constant of the horizontal accelerometer of the impact body	[-]
$\sigma_z$	vertical normal stress	[N cm <sup>-2</sup> ]
$\tau_y$	horizontal in plane shear stress	[N cm <sup>-2</sup> ]
$\tau_x$	horizontal out-of-plane shear stress	[N cm <sup>-2</sup> ]





