Development of Sensor Tights with Integrated Inertial Measurement Units for Injury Prevention in Football

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ABSTRACT In elite European football, 6 to 7 hamstring muscle injuries occur per team per season, which results in an absence of 14 to 180 days (Ekstrand, Waldén et al. 2017). These injuries occur typically in the last part of a training or match. This implies that the accumulation of demanding actions is an important factor for hamstring injury risk.

In current practice, physical player load is measured at the field by deriving the global location of the player with GPS and RFID systems. However, these systems are not able to monitor leg movement and to distinguish demanding actions like kicking, cutting and jumping.

In order to monitor these actions in the field, a novel design is being developed. The design consists of five sensor nodes with IMUs (Inertial measurement units), integrated in sports tights. IMUs can measure linear accelerations, angular velocities and magnetic fields in three directions. From these measurements, 3D kinematics of the lower limbs can be derived.

An iterative design approach is used to develop the tights. Four prototypes will be developed. Each prototype is tested in a football specific setting, to identify areas of improvement from a technical point of view as well as from a user's perspective.

The final aim of this research is to develop sensor tights that can be worn unobtrusively by football players in the field. Real-time data are retrieved by the coach. This allows the coach to intervene when there is a high injury risk.

Keywords: wearable sensors; injury prevention; smart clothing

Introduction

Football is played by more than 260 million people worldwide (Fédération Internationale de Football Association 2007). During an elite football game, players run about 10 km at 80 to 90 percent of their maximal heart rate. Numerous explosive actions take place, including high intensity sprints (which are quick accelerations followed by deceleration), turning, tackles, jumping, kicking and sustaining forceful contractions to maintain balance of the body and to control the ball (Stølen, Chamari et al. 2005).

Hamstring injuries in football

As explained above, physical player load is very high, which results in a high rate of injuries. Overuse injuries are in most cases located in the hamstrings, groin, knee and lower leg. Hamstring injuries are the most common injuries in football. Each season, 6 to 7 hamstring injuries occur in each professional team (Ekstrand, Waldén et al. 2017). The hamstring muscle group is situated at the back of the thigh and helps to extend the hip and to flex the knee. A hamstring injury is a strain or tear to the tendons or the muscles of this muscle group.

Measuring player load

The International Football Association Board (IFAB) decided in 2015 to allow wearable technology on the field. However, safety concerns have been raised and some sports organizations even banned existing electronic systems (Daniel, Eduard et al. 2017). Therefore, it is of great importance to create products that are safe to use.

Several products exist that can measure physical player load or performance at the moment, e.g. camera systems (e.g. Prozone Sports Ltd ®, UK), GPS systems (e.g. Catapult Sports Ltd, Australia and Zephyr Performance Systems, US) or RFID Systems (Inmotio Object Tracking, NED). Data for these systems can be used to derive the athlete's velocity or to classify activities, as shown in a study regarding classification of activities of elite female football players (Datson, Drust et al. 2017). Other systems like the LPM (local position measurement) system of Inmotio are equipped with an accelerometer and can measure average acceleration and deceleration quite accurately (Stevens, Ruiter et al. 2014).

However, in order to be able to obtain information about the actual player load, we need to have detailed information of the local upper and lower limb accelerations and forces and not just the speed and global position of the athlete.

Therefore, this research proposes the design of a new product with integrated sensors that can measure linear accelerations, angular velocities and the earth magnetic field at the lower and upper legs. The sensor data can be used to obtain the orientation of each leg segment real-time. In this way the exact movement of the leg can be detected, which provides better insight in the load at the hamstring muscles to prevent injuries in the future.

The Designer's role

The research project about the development of the new sensor tights, involves several disciplines. Two human movement scientists are working fulltime on translating the sensor data to valuable information or parameters to predict injury risk. A sports doctor and an embedded scientist are involved to monitor the applicability in a real sports setting. An electrical engineer, software engineer and a smart textile researcher are working on the hardware and software of the tights.

The specialists in the team are responsible for certain parts of the design. The role of the designer is to lead the design process by stimulating ownership by the specialists of the subsystems, while keeping challenging them to consider the perspectives of the other stakeholders. Integration of the subsystems is done by the designer with the application in mind.

The two main research questions that need to be answered are:

1. How can we reliably measure leg segment movement during football with IMUs?
2. How can we create an easy-to-use and comfortable wearable that has a high acceptance rate among football players?

Method

A participatory design approach (Dell'Era and Landoni 2014) was followed. The users in this stage are human movement scientists, embedded scientists and sports doctors and in this project, they are a 'partner' in the development process. The movement scientists are involved in every main decision in the design process. Professional football players, who will wear the product, are also observed and consulted from the start of the development process.

1. Analysis phase: List of criteria

To create a complete list of requirements several stakeholders are interviewed, including movement scientists, sports doctors, physiotherapists and professional football players (figure 1). Furthermore, a series of football trainings is observed, and actions are counted, to get an idea of the type and quantity of actions that are involved when the product is worn. The total observation time is 90 minutes.

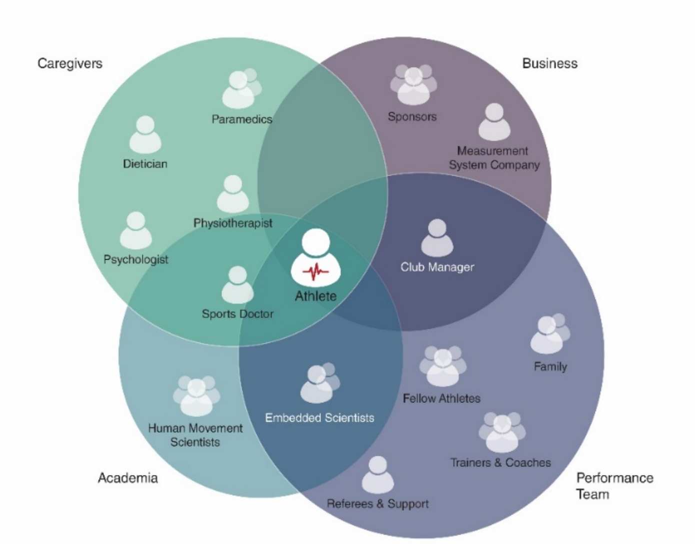

Figure 1. Stakeholder Map

2. Design phase

During the design phase, an iterative design approach is used. The project timespan is 4 years and every year a new, improved prototype is planned to be created. These are the main milestones. Quick prototype to test subsystems are made in between as well. Figure 2 shows the project plan and the current status of the project.

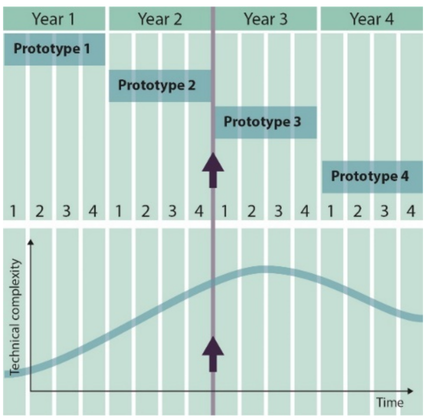

Figure 2. Project plan: the purple arrow shows the current status

In this paper we describe the design and development of prototype 1 and 2.

The first three prototypes are research prototypes for the human movement scientists. These prototypes are used as a measurement tool to identify hamstring injury risk factors. Since these prototypes are used for scientific research, the technological demands (e.g. sample frequencies and measurement ranges) are high. Once hamstring injury risk factors are identified and the required specifications of the sensor tights are known, the final product will benefit from this knowledge and can possibly be simplified. This will decrease the threshold to production and sales and increase acceptance by amateur football teams. The final product will be used by sports coaches, trainers and athletes.

3. Evaluation

To answer the two research questions, the evaluation of each prototype consists of two parts: the technical validation and user experience tests. Insights of these tests are used in the improved design of the next prototype.

3.1. Technical validation

For testing the status of the reliability of the system, each prototype is validated according to the following protocol at the KNVB Campus (Zeist, The Netherlands) (Bastiaansen, Brink et al. 2019, Wilmes, Ruiter et al. 2019).

Different football specific movements are executed, such as a jump, kick, acceleration run and deceleration run, at different intensities (low, medium, high). The movements are recorded by a VICON system (assumed to be the golden standard in movement tracking) and by the sensor tights. The sensor data are translated to orientation data with a biomechanical model developed by the movement scientists. Joint angles (Figure 3) of both systems are compared and root means square errors (RMSEs) are calculated.

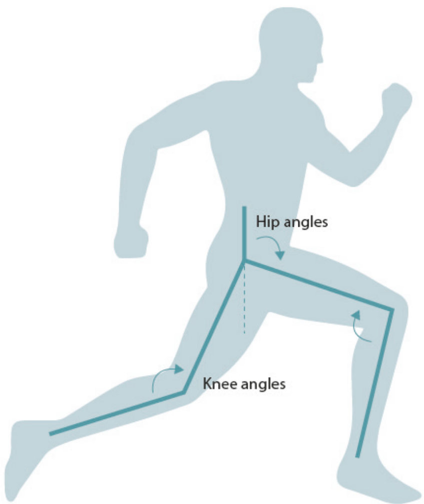

Figure 3. Visualisation of joint angles of interest

3.2 User Experience tests

To test the degree of comfort and ease-of-use, the tights will be worn in trainings too. Wearers are asked about their experience and if they feel restricted by the tights through a short questionnaire. The human movement scientists, who are identified as the users at this stage, are also asked about their experience in using the product. Questions about ease of use are asked.

Results

1. Analysis phase: List of criteria

Below, the most important criteria for the development of the sensor tights are highlighted:

1. Five IMUs are integrated in the pants, one at the trunk, one at each upper leg and one at each lower leg. They gather accelerometer data, gyroscope data and magnetometer data in x,y,z directions.

2. Raw data are saved and can be read out at a computer.

3. The electronics will not harm the wearer and fellow players during a match.

4. The product is comfortable to wear and does not restrict the athlete's movements.

5. The IMUs do not move with respect to the skin.

2. Design phase

To identify the best sensor locations, a trade-off was made between minimizing the risk of soft tissue artefacts (STAs), which increases technical reliability, and using a safe and comfortable location in a football context.

Based on the observations of the trainings, it was found that the following types of physical contact occur the most: duel face-to-face (A), duel face-to-back (B) and duel side-to-side (C). This type of contact is often limited to the feet and arms. In training exercises that involve physical contact, this was 0.064 (A), 0.046 (B) and 0.084 (C) times per player per minute. Slidings, which can potentially move or break the sensors, occurred 0.008 times per player per minute. From a soft tissue artefact study, it was concluded that sensors at the side of the thigh and shank, show the lowest soft tissue artefact.

To find the best sensor locations, several consultation sessions where held with the movement scientists. Figure 4. shows some visual material that was used in the sessions.

Figure 4. Material used in the consultation sessions

Although physical contact may occur at the side of the thigh during trainings, this location was chosen for the upper leg sensors to keep STAs low. The lower leg sensors are placed at the inner sides of the shanks, near the knee. The central processing unit, containing the battery, microcontroller and SD card was placed above the sacrum.

Prototype 1

Prototype 1 (Figure 5) uses an Arduino Due (Arduino, USA) and the 9 DOF IMU sensor MPU9250 (Invensense, USA). These components are chosen to enhance quick prototyping. The MPU5250 sensor is widely used in movement tracking, but measurement ranges are limited (16g, 2000°/s). Wires are sewn to commercial tights in a serpentine pattern to allow stretchability and the sensors are encapsulated in silicone rubber to minimize injuries during player to player or player to ground contact.

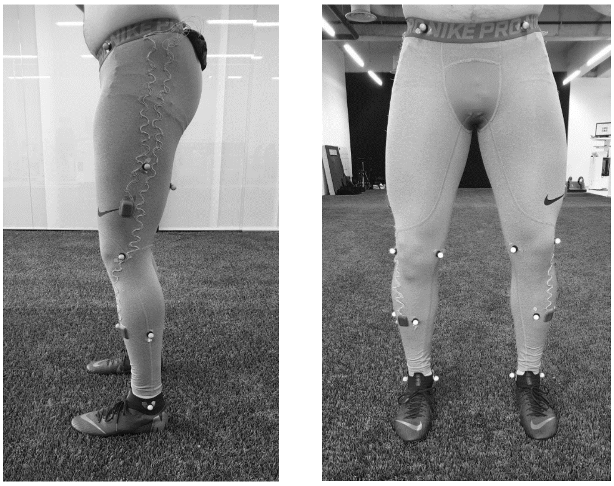

Figure 5. Prototype 1. Sensors are the black square units connected to the wiring; the white spheres are reflectors of the VICON system

Prototype 2

Prototype 2 (Figure 6) uses an STM32 microcontroller (STMicroelectronics, Switzerland), the ICM20649 IMU (Invensense, USA) and the AK8963 magnetometer (AKM Semiconductor, USA). Printed circuit boards (PCBs) are custom-made. Strips of fabric are patterned on commercial tights (Figure 7). Teflon coated stranded copper wires are laced in the strips in a serpentine pattern. The wiring is connected to the PCBs with wire-to-board connectors. Little sleeves are placed at the tights to hold the sensors and a larger pocket was created for the central processing unit.

Figure 6. Second prototype of the sensor tights

Washing tests with the connectors and wiring were executed. Prototype 2 is washable for at least ten times, when the sensor nodes and central unit are disconnected. The measurement ranges of the sensors are larger (32g, 4000°/s). The electronics are integrated better and higher sample frequencies can be reached (>250Hz) compared with prototype 1 (150Hz).

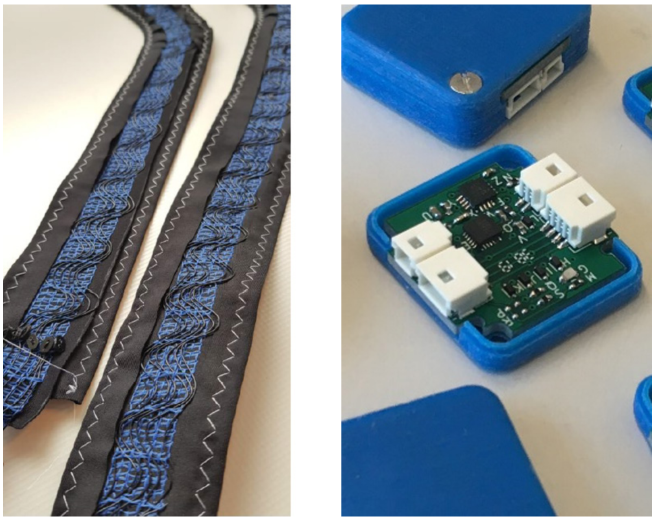

Figure 7. Left: wiring laced in strips of textile, right: the sensor node (21*24*8 mm, and 3.6 gramms)

3. Evaluation

At this moment, prototype 1 is validated and the prototype 2 is ready for validation.

3.1. Technical validation prototype 1

From the technical validation of prototype 1, it was found that RMSEs of the hip and knee flexion/extension angles are around 5 degrees (Vinasithamby 2019). Thus, concurrent validity with the VICON system is good. However, RMSE increases with exercise intensity. Besides, the maximal sample frequency is ± 150 Hz. This is relatively low, compared to commercial IMU systems, which can have a sample frequency of ± 250 Hz.

3.2. User experience prototype 1

Wearers of the tights (n=3, male, amateur football players, 20-40 yrs. old) mentioned that they did not feel the sensors and they did not feel restricted in their movements by the tights. However, there was a risk to get entangled with the wiring. Moreover, the pocket that contained the Arduino and battery, shook during exercises which was experienced as mildly uncomfortable. These comments are taken into consideration for the next prototype.

Discussion

The observations of football trainings gave insight in where the sensors could be placed to ensure safety and comfort. However, STAs need to be considered as well. To identify the best locations of the sensors for these first prototypes, a trade-off was made. The sensors at the thigh, can potentially be a problem in duels and with slidings. Therefore, it would be interesting to investigate slightly different locations, for example closer to the knee.

Insights from the development and evaluation of prototype 1 are used in the development of prototype 2. The central unit for prototype 2 is much smaller, more robust and more compact. Furthermore, the wiring is covered by a layer of textile to prevent entanglement.

For prototype 2, a user interface with some buttons and LEDs was added. With the interface, the user can start and stop measurements, highlight certain activities and show the status of the device. The current interface will be tested and improved based on user tests. For prototype 3 it is considered to change the buttons and LEDs based on the feedback from the user tests.

At this moment, the product provides the user, now still a scientist, with the raw data through an SD card. Once we know more about the hamstring injury risk factors based on the research of the movement scientists, a design project can be initiated about how we can communicate these data to the coaches and trainers. It needs to be considered to show the information to the football players too.

A concern that needs to be mentioned is that, during the interviews with professional football players, they reported unanimously that they were not going to wear tights during a public game. It appears that playing with bare legs is customary in current football culture. To increase acceptance among football players, the appearance of the product must change. Shorts are a better option, but the lower leg sensors are still required for research purposes. For the next prototypes it will be discussed whether shorts will be the final product and if separate wireless sensors, for example in the shin guards, are required.

In short, a 2nd fully working prototype of the sensor tights is developed and will be evaluated in a technical validation study and user experience tests. Future prototypes will focus on even better integration of electronics and washability. In a later phase, a user interface to show hamstring injury risk will be developed in collaboration with the human movement scientists.

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