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ORIGINAL ARTICLE

A wearable sweat rate sensor to monitor the athletes' performance during training

Mise au point d'un capteur de mesure de la sudation durant l'entraînement

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Sweat rate;
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Summary
Objectives. — We developed a wearable sensor for the real time measurement of sweat rate in localized areas of the human body. This sensor represents the first step in the development of a wearable sensor network capable to estimate the global sweat rate via an ad hoc algorithm. Such device would be used to monitor athletes' hydration status during training and improve their performances.
Equipment and methods. — For this study, we tested our sensor on thirteen football players during a cycling test on a cycle ergometer. The sweat rate sensor was compared to a medical device that, although measuring a different physiological process, provides discrete data based on the same working principle, i.e. the diffusion of the water vapour emitted from the skin.
Results. — Our sensor has a working range up to 400 g/m^2·h. The statistical analysis and the Bland-Altman plot proved that our sensor is comparable to the medical device used as gold standard. At low sweat rate, the bias is 3.4 g/m^2·h with a standard deviation of 7.6 g/m^2·h. At maximum sweat rates, the bias is 2.3 g/m^2·h with a standard deviation 6.9 g/m^2·h. The *P*-values for the Bland-Altman plots at low and maximum sweat rate (0.1331 and 0.2477 obtained by Kolmogorov-Smirnov test, respectively) allow the hypothesis that there is a significant difference between our sweat rate sensor and the medical device to be rejected.

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Conclusion. — We presented a prototype of a wearable sweat rate sensor for localized measurements. The trials on thirteen athletes proved that the performance of our sensor is comparable to that of a commercial medical device. This sweat rate sensor can provide valuable information on athletes' hydration status.

MOTS CLÉS
Débit sudoral ;
Performance sportive ;
Entraînement personnalisé ;
Capteur portable ;
Hydratation

Résumé
Objectifs. — Nous avons développé un capteur portable pour mesurer le taux de sudation en temps réel dans des zones précises du corps humain. Ce capteur pourrait conduire à un réseau portable, afin d'estimer le débit sudoral global, via un algorithme ad hoc, pour surveiller l'état d'hydratation des athlètes lors de l'entraînement, et ce afin de maintenir leurs performances.
Matériel et méthodes. — Pour cette étude, nous avons testé notre capteur sur treize joueurs de football au cours d'un exercice sur bicyclette ergométrique. Le capteur d'évaluation du débit sudoral a été comparé à un dispositif médical qui, bien que mesurant un processus physiologique différent, fournit des données discrètes basées sur le même principe de fonctionnement, à savoir la diffusion de la vapeur d'eau émise par la peau. Résultats Notre capteur a une capacité de fonctionnement jusqu'à 400 g/m^2·h. L'analyse statistique et graphique de Bland-Altman montre que notre capteur est comparable au dispositif médical utilisé comme référence. Avec un taux de sudation bas, le biais est de 3,4 g/m^2·h avec écart type de 7,6 g/m^2·h. Avec un taux de sudation maximal, le biais est de 2,3 g/m^2·h avec un écart type de 6,9 g/m^2·h. La comparaison statistique des graphiques de Bland-Altman, pour des débits sudoraux faible et maximum (valeurs respectives de $p = 0{,}1331$ et $p = 0{,}2477$) permet de rejeter l'hypothèse selon laquelle il existerait une différence significative entre notre capteur de sudation et le dispositif médical.
Conclusions. — Nous proposons un prototype de capteur de débit de sudation portable pour les mesures localisées. Cet essai sur treize athlètes a montré que la performance de notre capteur est comparable à celle du dispositif médical commercialisé. Ce capteur de débit de sudation peut fournir des informations précieuses sur l'état d'hydratation des athlètes.

1. Introduction

The production and evaporation of sweat from the skin's surface is essential to regulate temperature in the human body and maintain homeostasis [1]. Sweat occurs with the activation of eccrine glands and the rate depends on the emitted amount per gland [2]. Eccrine glands are unevenly distributed on the skin and their number ranges between about 1.6 and 4 million. The palms of hands and the soles of feet have the highest density (600—700 glands/cm^2), whereas other parts of the human body have a density that is less than one third lower, e.g. 108 glands/cm^2 on the forearm and 181 glands/cm^2 on the forehead [3]. At 25 °C and a relative humidity of 50%, the average sweat rate in adults is about 500—700 mL/day with a maximum of 1.4 L/h or 20 nL/min per gland [1,3,4].

Although exceptional values of sweat rates are possible, e.g. 1 L for 15 min in saunas or more than 3L/h during preparation for a marathon [3,5], the human body can only sustain high sweat rates for a short period. Despite its crucial role in thermoregulation, there is a side effect of sweat production. During sweating, the body loses fluids that need to be replaced to maintain the correct functionality of the physiological processes inside the human organism. In fact, sweat consists of about 99% water and about 1% electrolytes, mainly sodium, chloride and potassium [6]. Therefore, especially during exercise or intense training, there is a concrete risk of dehydration [7,8]. Although there are athletes who can tolerate fluid losses of 4%—5% of body mass, in normal subjects, values between 1% and 2% of body weight already start to alter the normal physiological conditions [9]. Higher values of dehydration affect the cardiovascular system, causing for example heat cramps or heatstroke [10].

The electrolytes lost during sweating are indispensable to preserve and maintain blood pressure, plasma volume, the transmission of nerve impulses and normal cell activities [11—13]. The correct replenishment prevents abnormal physiological conditions, which can also be potentially life threatening. During a competition, athletes can only rely on their feelings and experience to match their physical efforts to their physical conditions. Hence, knowing their sweat rate values would help athletes in achieving optimum performance while avoiding possible health complications.

Measuring the sweat rate is challenging and currently there is no technique to determine sweat rate outside controlled laboratories during the subject's normal life or training [14]. In the iodine starch method, some iodine powder is sprayed on the skin. In contact with sweat, the colour of the powder turns dark purple [15]. However, this method can only be used for assessing the presence of sweat. The wash-down method involves the construction of a plastic frame that supports a large plastic bag within which the subject exercises with a cycle ergometer. Before the beginning of the exercise, the subject and the bag are washed with deionized water. When the exercise is completed, the subject and the bag are washed with water containing