On Sweat Analysis for Quantitative Estimation of Dehydration during Physical Exercise

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***Abstract*— Quantitative estimation of water loss during physical exercise is of importance because dehydration can impair both muscular strength and aerobic endurance. A physiological indicator for deficit of total body water (TBW) might be the concentration of electrolytes in sweat. It has been shown that concentrations differ after physical exercise depending on whether water loss was replaced by fluid intake or not. However, to the best of our knowledge, this fact has not been examined for its potential to quantitatively estimate TBW loss. Therefore, we conducted a study in which sweat samples were collected continuously during two hours of physical exercise without fluid intake. A statistical analysis of these sweat samples revealed significant correlations between chloride concentration in sweat and TBW loss ($r = 0.41$, $p < 0.01$), and between sweat osmolality and TBW loss ($r = 0.43$, $p < 0.01$). A quantitative estimation of TBW loss resulted in a mean absolute error of 0.49 l per estimation. Although the precision has to be improved for practical applications, the present results suggest that TBW loss estimation could be realizable using sweat samples.**

I. INTRODUCTION

Increased metabolism and muscle activity during physical exercise produce heat which has to be dissipated in order to defeat hyperthermia [1]. This heat is transported with blood flowing from core body and muscles to the skin, where heat can be dissipated by secreting sweat via eccrine sweat glands [2], [3]. The sweat consists to 99% of water [4], and with every 1 mL of water evaporating on the skin, 2.4 kJ of heat are released to the environment [5].

Besides water, there are electrolytes, like sodium (Na^+) and chloride (Cl^-), among the remaining constituents of sweat [6]. This is because the precursor fluid for sweat originates from blood plasma where these electrolytes are solved in form of ions [7]. But on the sweat's way from blood plasma to skin surface, electrolytes are partly reabsorbed in the duct of eccrine sweat glands in order to defeat the dangerous loss of electrolytes [3], [6]. Therefore, Na^+ and Cl^- concentrations are lower in sweat that finally appears on the skin than in blood [6], [8].

Recently, Morgan et al. [9] analyzed sweat composition after two hours of physical exercise in two situations. In the first situation, subjects were asked to replace water loss by drinking a NaCl solution. In the second situation, subjects were not allowed to drink anything. Morgan et al. [9] observed that Na^+ and Cl^- concentrations were elevated in sweat when fluid intake was forbidden. An explanation might be that reabsorption was reduced in the duct when drinking was forbidden. However, changes in reabsorption behavior are primarily known when sweat rate changes [10]. In the study of Morgan et al. [9], no difference was observed in sweat rate. Another explanation might be provided by the fact that Na^+ and Cl^- concentrations were elevated in blood serum when drinking was forbidden [9]. Because sweat originates from blood, this could have caused elevated Na^+ and Cl^- concentrations in sweat. The elevated Na^+ and Cl^- concentrations in serum were unlikely to be caused by a higher, absolute amount of Na^+ and Cl^-, since both ions were lost through sweating. Instead, Na^+ and Cl^- concentrations might have increased because the body's entire blood volume decreased due to (blood) water loss through sweating [7]. This reduced the blood volume in which Na^+ and Cl^- ions could distribute and increased their concentration.

Summarizing these physiological processes, Na^+ and Cl^- concentrations in sweat seem to reflect (blood) water loss due to sweating. Therefore, we hypothesized that electrolyte concentrations can be employed to quantitatively estimate dehydration during physical exercise. For this purpose, a study was conducted in which sweat samples and reference measurements of total body water (TBW) loss were recorded during a two-hour running workout. In contrast to the study of Morgan et al. [9], in which only one sweat sample was collected over two hours, the present study collected sweat samples every 15 minutes. The analysis of these samples and their predictive ability to estimate TBW loss during physical exercise is the subject of the present paper.

II. METHODS

This section describes the data collection study, a statistical analysis of the sweat samples and their relationship to TBW loss, and a regression method to quantitatively estimate TBW loss using the sweat samples.

A. Data Collection

In the data collection study, various physiological quantities were measured. Because the present paper focuses on sweat, study details that are not relevant to this focus are omitted in the following outline.[1]

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[1]The full study protocol may be found in the International Clinical Trails Registry Platform of the World Health Organization: http://apps.who.int/trialsearch/Trial2.aspx?TrialID=DRKS00005301.

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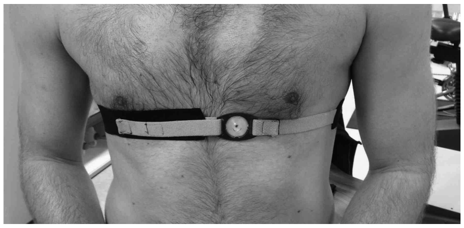


Fig. 1. Exemplary image of sweat collection: the sweat collector was fixed with a strap below the left m. pectoralis major.

1) Subjects: Ten male subjects (179 $\pm$ 7.5 cm; 79.3 $\pm$ 9.0 kg; 25.5 $\pm$ 3.7 years) volunteered to participate in the study. All subjects provided written informed consent after the study protocol was approved by the local ethics committee.

2) Preparations: For comparable physical effort among different subjects, the subjects' individual ventilatory threshold (VT) and, if possible, maximum oxygen uptake (VO_{2max}) were determined (according to [11]). The determination of VT and VO_{2max} was conducted at least one day and at most one week before the data collection study. In the data collection study, running speed for every subject was then set to the speed that corresponded to $\min(\mathrm{VT}, 60\%\ \mathrm{VO}_{2\max})$.

Similar to the study of Morgan et al. [9], three requirements were defined so that all subjects began the data collection study in an identical hydration condition. First, subjects were asked to refrain from exhausting physical exercise, alcohol, and caffeine on the day before. Second, subjects were asked to report to the laboratory at 6:30 in the morning, after a ten-hour overnight fast. In the laboratory, all subjects received an identical breakfast: 250 ml of apple juice mixed with water after arrival, and 312 ml of a meal replacement drink one hour later (Fit and Feelgood Diät-Shake, Layenberger, Rodenbach, Germany). Third, subjects were not allowed to eat or drink anything else until the end of the data collection study.

3) Data Collection: Data was collected during a two-hour running workout on a treadmill, starting at 9:30. The treadmill was placed in a laboratory with standard room temperature and humidity. All subjects wore identical t-shirts and shorts (Response 3-Stripes, Adidas, Herzogenaurach, Germany) in order to avoid confounding effects of clothing on sweating.

The workout procedure was arranged so that periodic measurements could be recorded, while subjects were continuously loosing water because of the physical effort. For this purpose, the two hours of running were partitioned into eight intervals of 15 minutes. Every interval was followed by a break of 8 minutes, in which sweat samples were collected and reference measurements of TBW loss were recorded.

In the following, variables are indexed with i, where $i = 0$ denotes baseline measurements before running began, and $i = 1, \ldots, 8$ denotes measurements after the i-th interval.

4) Sweat Samples: Sweat was collected below the left m. pectoralis major using Macroduct sweat collectors (Wescor, Logan, UT, USA); see Fig. 1. During every 15-minute running interval, a collector was fixed with a strap around the chest. In the break after every interval, the collector was removed, the subject was asked to remove all sweat on his body using a towel, and a new collector was attached.

Cl^- concentration was analyzed with a chloridometer (CM20, Kreienbaum, Langenfeld, Germany). Na^+ was not analyzed because Na^+ and Cl^- are highly correlated [12]. Instead, osmolality was analyzed with a vapor pressure osmometer (Vapro, Wescor, Logan, UT, USA). Osmolality is a measure for the total amount of electrolytes in sweat, including Na^+ and Cl^-. In some samples, Cl^- concentration or osmolality could not be analyzed, because not enough sweat entered the collector during the 15-minute interval. In such cases, missing values were linearly interpolated using the other, available values of the subject. More advanced interpolation techniques were not considered because at most seven data values were available for every interpolation.

In the following, c_i^{Cl} denotes Cl^- concentration in the i-th interval (in mmol/l), and c_i^{Osmo} denotes osmolality in the i-th interval (in mmol/kg).

5) TBW Loss: Reference measurements of TBW loss were recorded using the following method [13]: If there is no fluid and food intake, and no urine and fecal losses, then TBW loss is identical to nude body weight loss. Thus, subjects were asked to take off their clothing and remove all sweat on their body with a towel. Then, nude body weight was measured over 15 s using a high-precision scale ($\pm$ 5 g accuracy; DE 150K2D, Kern & Sohn, Balingen-Frommern, Germany). Nude body weight was averaged over the 15 s, and TBW loss after the 15-minute interval was set identical to body weight loss after the interval. Nude body weight was also measured immediately before treadmill running began.

In the following, W_0 denotes nude body weight before running began, and W_i denotes nude body weight after the i-th interval. Then, $V_i^{\mathrm{TBW}} = W_0 - W_i$ denotes TBW loss after the i-th interval, with respect to the beginning of the workout.

B. Statistical Analysis

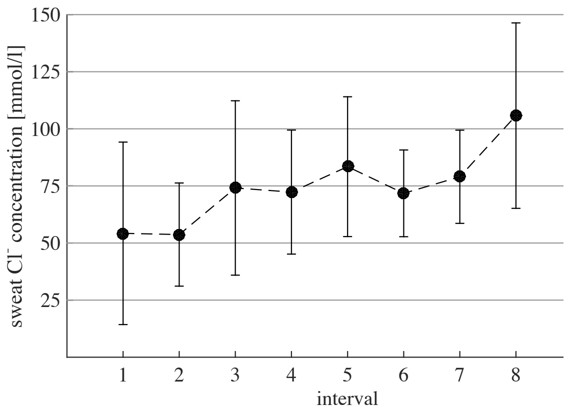
The physiological relationship between electrolytes in sweat and TBW loss was outlined above. On basis of the collected data, this relationship was examined using Pearson's product-moment correlation coefficient r [14, Ch. 1]. The coefficient was computed between Cl^- concentration and TBW loss, denoted as r^{Cl}, and between osmolality and TBW loss, denoted as r^{Osmo}. Both correlations were tested against the null hypothesis of no correlation, and the significance level was set to $\alpha = 0.01$.

C. Quantitative Estimation of TBW Loss

TBW loss was estimated using Gaussian process regression (GP, [15, Ch. 2]). The inputs were two-dimensional vectors $\mathbf{x}_i = \left(c_i^{\mathrm{Cl}}, c_i^{\mathrm{Osmo}}\right)$, describing Cl^- concentration and osmolality in the i-th interval. The targets were the corresponding TBW losses V_i^{TBW}. Hence, the GP learned a function

$$f(\mathbf{x}_i) = V_i^{\mathrm{TBW}} \tag{1}$$

to estimate TBW loss using Cl^- concentration and osmolality.



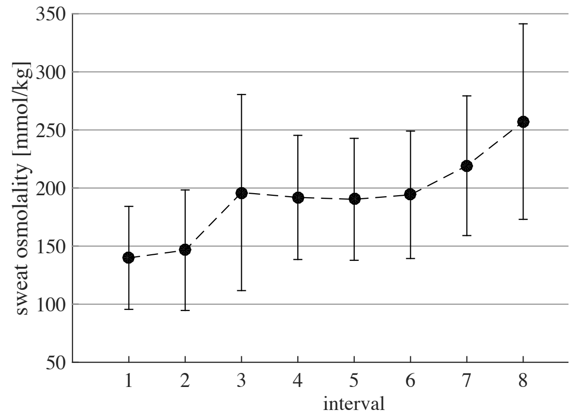


Fig. 2. Progression of Cl^- concentration (left) and osmolality (right) over the eight running intervals. Both plots depict mean and standard deviation after averaging over all subjects.

In detail, input and target values were first normalized to the numerical range [0;1]. Then, a GP was trained using an affine mean function and a squared exponential covariance function. The parameters of the mean function were initialized with 0.1 (slope) and 0 (offset). The parameters of the covariance function were initialized with 1 (characteristic length-scale) and 1 (signal standard deviation). The standard deviation of noise in the Gaussian likelihood function was initialized with 0.1. Then, all parameters were optimized by minimizing the negative log likelihood using a conjugate gradient descent (maximum 1,000 iterations). This GP setting using a squared exponential covariance function was selected to enable modeling of possible nonlinear relationships among the inputs.

This approach was evaluated using a leave-one-subject-out cross-validation (LOSO-CV, [16, Ch. 7]). In brief, a LOSO-CV declares every subject once as testing subject, whereas the remaining subjects are declared as training subjects. Then, a GP is trained on all input-target pairs $\left(\mathbf{x}_i, V_i^{\text{TBW}}\right)$ from the training subjects. Using this GP and the inputs $\mathbf{x}_i = \left(c_i^{\text{Cl}}, c_i^{\text{Osmo}}\right)$ from the testing subject, TBW loss after every interval is estimated for the testing subject.

The performance of this method was evaluated using two measures. The first measure illustrates performance per subject, whereas the second measure illustrates performance per interval. In detail, for the first measure, the absolute difference between estimated TBW loss and reference TBW loss was computed for every interval and every subject. These absolute differences were averaged over all eight intervals for every subject. For the second measure, estimated TBW loss after every interval as well as reference TBW loss after every interval were averaged over all subjects.

III. RESULTS

A. Statistical Analysis

The progression of Cl^- concentration and osmolality over the eight intervals is depicted in Fig. 2. Both quantities increased over time but with a rather high standard deviation. The correlation coefficient between Cl^- concentration and TBW loss was $r^{\text{Cl}} = 0.41$ ($p < 0.01$). The correlation coefficient between osmolality and TBW loss was $r^{\text{Osmo}} = 0.43$ ($p < 0.01$).

B. Estimation of TBW Loss

Table I reports the error of TBW loss estimation per subject. The most accurate estimation of TBW loss was achieved for subject no. 10 with an average error of 0.12 l per interval. In contrast, the most imprecise estimation of TBW loss was achieved for subject no. 3 with an average error of 0.95 l per interval.

Fig. 3 depicts progression of TBW loss over the eight intervals. Predicted TBW loss increased over the eight intervals, similar to reference TBW loss. However, at the beginning, TBW loss was overestimated, whereas at the end, TBW loss was underestimated.

TABLE I

ABSOLUTE ERROR OF TBW LOSS ESTIMATION PER SUBJECT, AVERAGED OVER ALL EIGHT RUNNING INTERVALS

Subject	Absolute Error [l]
1	0.56 ± 0.36
2	0.55 ± 0.37
3	0.95 ± 0.39
4	0.49 ± 0.37
5	0.26 ± 0.14
6	0.28 ± 0.29
7	0.56 ± 0.36
8	0.68 ± 0.57
9	0.47 ± 0.52
10	0.12 ± 0.09
mean ± std	0.49 ± 0.23

IV. DISCUSSION

The present study collected sweat during physical exercise and analyzed progression of Cl^- concentration and osmolality over time. Significant correlations between these two physiological quantities and TBW loss were observed. Furthermore, a computational experiment was conducted to investigate if TBW loss can be estimated using Cl^- concentration and osmolality.

To the best of our knowledge, this was the first study to analyze Cl^- concentration and osmolality continuously during progressive dehydration. The significant correlation between Cl^- concentration and TBW loss, and between osmolality and TBW loss confirmed the hypothesis that these two quantities could be used to estimate TBW loss. However, the computational experiment achieved no satisfactory results (Table I). Although the general trend of TBW loss was estimated correctly (Fig. 3), the present approach would be too imprecise for practical usage.

An explanation might be given by the fact that both Cl^- concentration and osmolality are known to vary considerably among individuals [8]. The present approach utilized Cl^- concentration and osmolality from a set of training subjects to estimate TBW loss for a testing subject. Maybe this approach was not sufficiently individualized or a larger amount of training subjects would have been required. Furthermore, the variability among individuals might also explain the high standard deviation which has been observed in Cl^- concentration and osmolality over time (Fig. 2).

Therefore, further research is required to exploit the observed correlations for the purpose of precise TBW loss estimations. A simple approach might be the usage of relative changes in Cl^- concentration and osmolality instead of absolute changes as in the present study. A more sophisticated approach might be the inclusion of another physiological quantity which helps to classify individual Cl^- concentration and osmolality. For example, Cl^- concentration and osmolality could be measured in blood before physical exercise begins. Since sweat originates from blood, this might help to explain the variability of initial Cl^- concentration and osmolality as well as their progression over time. Sweat rate might also help to explain variability since reabsorption in the duct is known to be influenced by sweat rate [10]. Finally, further studies that also investigate different types and intensities of physical exercise will be necessary before sweat analysis can be used for TBW loss estimation in practice.

V. SUMMARY

This paper analyzed Cl^- concentration and osmolality in sweat during progressive dehydration due to physical exercise. Significant correlations were found between each of these two quantities and TBW loss. A computational experiment was conducted to investigate if these correlations could be used to estimate TBW loss quantitatively. The results indicated that this approach might be realizable. However, future research will still be necessary to achieve precise estimations of TBW loss on basis of sweat samples.

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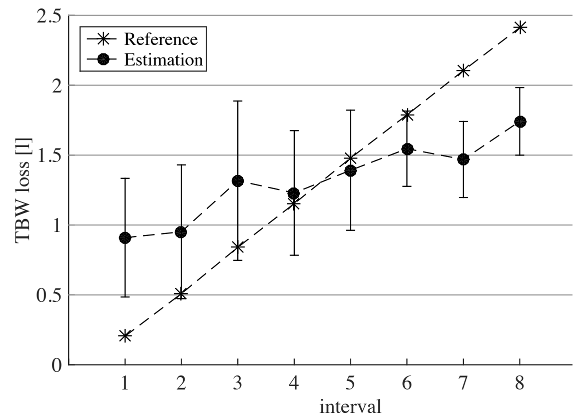

Fig. 3. Progression of estimated TBW loss and reference TBW loss over the eight running intervals. The plot depicts mean and standard deviation after averaging over all subjects.

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