A Two-Stage Regression Using Bioimpedance and Temperature for Hydration Assessment During Sports

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***Abstract*—Bioimpedance analysis (BIA) estimates the amount of total body water (TBW) in the human body. During sports, however, the increased skin temperature distorts bioimpedance measurements and, thus, prevents the application of BIA. In this paper, we propose a two-stage regression that includes temperature information in order to correct the temperature-distorted bioimpedance. In detail, the first regression stage corrects temperature-distored bioimpedance using information of skin and core temperature. The second regression stage estimates TBW loss on basis of the corrected bioimpedance. The two-stage regression was evaluated using data of an ongoing study. The results showed that estimations of TBW loss during sports can be considerably improved if temperature information is included. However, a remaining error was still observed. Therefore, additional measurements, e.g., skin blood flow, are discussed because they also influence bioimpedance and could further reduce the error.**

I. Introduction

The human body of an average 75-kg male consists of 45 l of water, which constitutes about 60% of the total body mass [1]. Various techniques exist to assess the amount of total body water (TBW) in the human body, e.g., isotope dilution, blood plasma analysis, or analysis of electrical impedance (bioimpedance) of the human body [2]. Among these, bio-impedance analysis (BIA) provides an accurate, easy-to-use, rapid, portable and noninvasive technique [3]. By now, research even focused on the integration of BIA devices into wearable textiles, e.g., t-shirts, to measure bioimpedance during daily life [4].

With these advantages, BIA would be an excellent option to assess TBW during sports and to identify dehydrated athletes. Identification of dehydrations is crucial in sports because, for example, a marathon runner may lose up to 14% of TBW in warm environments [5]. According to Schoeller [6], the loss of 15% of TBW is already life threatening.

Thus, several studies investigated the applicability of BIA during sports, however, with contradictory findings: some observed an increase of bioimpedance while others observed a decrease of bioimpedance [7]. Theoretically, an increase of bioimpedance should be observed because the body loses water through sweating: the less water (which contains electrolytes) in the body to conduct electrical current, the higher the bioimpedance [7].

The findings of decreased bioimpedance could be explained by the fact that increased skin temperature, which is usually present during sports, causes a decrease of bioimpedance [8], [9]. As a consequent continuation of this fact, the correction of bioimpedance using skin temperature was proposed for situations when BIA is applied in warm or cold environments [10].

In this paper, we apply the approach of temperature-based bioimpedance correction when BIA is applied during sports. In this situation, the bioimpedance is simultaneously influenced by increasing temperature and decreasing TBW. Therefore, we propose a two-stage regression (Sec. II). The first regression stage corrects temperature-distorted bioimpedance using information of skin and core temperature. The second regression stage estimates TBW loss on basis of the corrected bioimpedance. The two-stage regression was evaluated on data of an ongoing study (Sec. III). The results show that the error of TBW estimations could be reduced compared to TBW estimations without temperature information. However, we still observed a remaining error. Therefore, we also discuss possible reasons and suggest further steps to handle the remaining error (Sec. IV).

II. Methods

This section first reviews some fundamentals of BIA that form the basis of the proposed two-stage regression. Then, the study is outlined that was conducted to collect training data. Finally, a two-stage regression is proposed in order to apply BIA during sports.

A. Fundamentals of Bioimpedance Analysis (BIA)

BIA is based on the physical relation between the electrical resistance R of a homogenous conductor and its uniform cross-sectional area A, length l, and volume $V = Al$:

$$R = \rho \frac{l}{A} = \rho \frac{l^2}{V} \tag{1}$$

where ρ denotes the electrical resistivity of the conductor [3].

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BIA sets the length l to the body height H, estimates the electrical resistivity ρ, and assumes the volume V to be proportional to TBW. This assumption is based on the fact that water contains the electrolytes that conduct electrical current through the body. Therefore, BIA solves (1) for V and estimates the volume of total body water V^{BIA} (in liters) on basis of the relationship

$$V^{\text{BIA}} \propto \frac{H^2}{R}. \quad (2)$$

Usually, additional information of body weight W, age A, and sex S (e.g., $S = 1$ for males and $S = 0$ for females) is included. This leads to the common BIA equation

$$V^{\text{BIA}} = a_0 + a_1 \frac{H^2}{R} + a_2 W + a_3 A + a_4 S. \quad (3)$$

The coefficients a_i, $i = 0, \ldots, 4$, are estimated with multiple linear regression in a training process. The resistance R is retrieved by applying a small, alternating electrical current to the body and measuring the bioimpedance $Z = R + iX$, where i denotes the imaginary unit and X the reactance. Many BIA methods also replace the resistance R with the magnitude of the bioimpedance

$$|Z| = \sqrt{R^2 + X^2}. \quad (4)$$

Then, (3) becomes

$$V^{\text{BIA}} = a_0 + a_1 \frac{H^2}{|Z|} + a_2 W + a_3 A + a_4 S. \quad (5)$$

B. Subjects, Study Protocol, and Measurements

The study protocol was designed to collect several biomedical measurements, which are known to correlate with TBW, during sports. Because this paper concentrates on bioimpedance and temperature, the following description of the protocol only reports information relevant for this purpose.[1]

1) Subjects: Ten male subjects volunteered to participate in the study. All subjects provided written informed consent after the study protocol was approved by the local ethics committee. Up to now, six healthy subjects (24.5 ± 4.7 years, 183.4 ± 6.1 cm, 81.1 ± 3.8 kg; mean ± std) have completed the entire protocol.

2) Study Protocol: The study protocol consisted of two parts. In the first part, subjects underwent a physical examination[2]. In particular, the examination included determination of the subjects' anaerobic threshold (AT) and maximal oxygen uptake $VO_{2\text{max}}$. This first part was performed at least one day and at most one week before the second part of the study.

In the second part, several biomedical measurements were collected during a treadmill run, including bioimpedance, temperature, and TBW. Three requirements were defined to ensure that all subjects began the treadmill run equally hydrated. First, subjects were asked to refrain from strenuous physical activity, 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, consisting of 250 ml of apple juice mixed with water and 312 ml of a meal replacement drink (Fit and Feelgood Diät-Shake, Layenberger, Rodenbach, Germany). Third, subjects were not allowed to eat or drink anything else until the end of the study.

At 9:30, subjects began a two-hour treadmill run at an individual running speed. The running speed was defined as the minimum of the speed that corresponded to AT and the speed that corresponded to 60% $VO_{2\text{max}}$. The treadmill was placed in a laboratory with normal room temperature. All subjects wore the same t-shirts and shorts (Response 3-Stripes, Adidas, Herzogenaurach, Germany).

The two-hour treadmill run was designed so that regular measurements could be collected while the subjects' TBW slowly decreased because of the physical activity. Therefore, the two-hour run was divided into eight intervals of 15 minutes of running. Every 15-minute running interval was followed by an eight-minute break in which measurements were collected.

Furthermore, baseline measurements were collected immediately before the subjects began the two-hour run. The baseline measurements and the measurements in every break were identical, including bioimpedance, temperature, and TBW.

3) Measurements of Bioimpedance: The magnitude of the bioimpedance of the left arm, right arm, trunk, left leg, and right leg was measured with a BIA device (InBody 720, Biospace, Seoul, Korea). The magnitude of the whole-body bioimpedance[3] was calculated by summation over all segmental measurements [11].

4) Measurements of Temperature: Three types of temperature measurements were collected. First, core temperature was measured using an infrared ear thermometer (Thermoscan IRT 4520, Braun, Kronberg, Germany). Second, skin temperature was measured at the positions at which the BIA device applied the electrical current to the body and measured the resulting bioimpedance. These positions were the palms of the left and right hand, and the soles of the left and right foot. Third, skin temperature was measured at several positions to compute a mean skin temperature. These positions were the lower and upper arm, the lower and upper leg, the chest, and the back. Mean skin temperature was computed using the weighting

$$\begin{aligned} T^{\text{skin}} &= 0.3[0.5(T^{\text{chest}} + T^{\text{back}}) \\ &\quad + 0.5(T^{\text{lower arm}} + T^{\text{upper arm}})] \\ &\quad + 0.2(T^{\text{lower leg}} + T^{\text{upper leg}}). \end{aligned} \quad (6)$$

This corresponded to the weighting of Ramanathan [12] to compute mean skin temperature, adapted for our situation of additional measurement positions. All measurements of skin temperature were collected using an infrared thermometer (FTN, Medisana, Neuss, Germany).

5) Measurements of Total Body Water (TBW): TBW estimations of the BIA device were not valid during the two-hour

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

[2]Details of the examination as well as inclusion and exclusion criteria can be found in the full study protocol.

[3]The BIA device measured bioimpedance using alternating electrical current at frequencies of 1, 5, 50, 250, 500 and 1000 kHz. Since the bioimpedance at very high frequencies is best for TBW estimations [3], only measurements at the frequency of 1000 kHz were further processed.

run because of the increased skin temperature. However, they were still recorded to enable comparisons to TBW estimations of our proposed method.

To measure the real TBW loss during the two-hour run, the following assumption was used [2]: If there is no fluid or food intake, the reduction of body weight during sports is only due to water loss. Therefore, in every break, subjects were asked to dry their entire body with a towel to remove all sweat on their skin. Then, the subjects' nude body weight was measured with a high-precision scale (DE 150K2D, Kern & Sohn, Balingen-Frommern, Germany; ± 5 g accuracy). TBW loss was set equal to the difference between these body weights and baseline body weight.

C. A Two-Stage Regression

This section proposes a two-stage regression in order to apply BIA during sports. The first regression stage corrects the temperature-distorted bioimpedance that was measured during the two-hour run. The second regression stage uses the corrected bioimpedance and the BIA equation (5) to estimate TBW loss during the two-hour run.

1) Training Procedure: The two-stage regression estimates TBW loss compared to baseline TBW, instead of absolute TBW. This is because the reference values are only available as differences compared to baseline TBW (Sec. II-B5).

Let the index i, $i = 1, \dots, 8$, denote the measurements in the i-th break, and let the index value $i = 0$ denote the baseline measurements. Furthermore, let the index j, $j = j_1, \dots, j_5$, denote the five (out of the total six) subjects that are employed in the training procedure (c.f., evaluation procedure in Sec. II-C2).

Starting with the BIA equation (5), TBW loss compared to baseline TBW can be computed with

$$\begin{aligned} \Delta V_{ij}^{\text{BIA}} &= V_{0j}^{\text{BIA}} - V_{ij}^{\text{BIA}} \\ &= a_1 H_j^2 \left(\frac{1}{|Z_{0j}|} - \frac{1}{|Z_{ij}|} \right) + a_2 (W_{0j} - W_{ij}) \end{aligned} \tag{7}$$

for every subject j at every measurement i. Note that the intercept a_0, age term $a_3 A_j$, and sex term $a_4 S_j$ vanished because they remain constant for all measurements i.

However, to estimate the *real* TBW loss $\Delta V_{ij}^{\text{TBW}}$, the temperature-distored bioimpedance Z_{ij} has to be replaced with the corrected bioimpedance $Z_{ij}^{\star}$:

$$\begin{aligned} \Delta V_{ij}^{\text{TBW}} &= V_{0j}^{\text{BIA}} - V_{ij}^{\text{TBW}} \\ &= a_1 H_j^2 \left(\frac{1}{|Z_{0j}|} - \frac{1}{|Z_{ij}^{\star}|} \right) + a_2 (W_{0j} - W_{ij}), \end{aligned} \tag{8}$$

where V_{ij}^{TBW} denotes the *real* absolute TBW. The variable $Z_{ij}^{\star}$ denotes the result of the first regression stage, i.e., the bioimpedance that is corrected for the influence of increased skin temperature.

To correct the temperature-distorted bioimpedance, the first regression stage assumes that the correction can be accomplished by including the factor that causes the distortion, namely the increased temperature. To this end, let

$$e_{ij} = |Z_{ij}^{\star}| - |Z_{ij}| \tag{9}$$

define the error between the corrected bioimpedance $Z_{ij}^{\star}$ and the temperature-distorted bioimpedance Z_{ij}. The first regression stage assumes that this error e_{ij} can be estimated with a function

$$f(\vec{T}_{ij}) = e_{ij} \tag{10}$$

that only depends on the temperature measurements

$$\vec{T}_{ij} = (T_{ij}^{\text{ear}}, T_{ij}^{\text{skin}}, T_{ij}^{\text{left palm}}, T_{ij}^{\text{right palm}}, T_{ij}^{\text{left sole}}, T_{ij}^{\text{right sole}})^{\text{T}}, \tag{11}$$

where every T_{ij}^{position} denotes the temperature measurement at the corresponding position (Sec. II-B4).

To learn the function f, the errors e_{ij} and, hence, the reference values of the corrected bioimpedance $Z_{ij}^{\star}$ are necessary. These reference values can be computed by a reformulation of (8) to

$$|Z_{ij}^{\star}| = \frac{a_1 H_j^2 |Z_{0j}|}{a_1 H_j^2 - |Z_{0j}| \Delta V_{ij}^{\text{TBW}} + a_2 |Z_{0j}| (W_{0j} - W_{ij})} \tag{12}$$

because all variables on the right hand side were measured. The height H_j, baseline bioimpedance Z_{0j}, body weights W_{0j} and W_{ij}, and in particular, the *real* TBW loss $\Delta V_{ij}^{\text{TBW}}$ (Sec. II-B5) were all measured.

Furthermore, the coefficients a_1 and a_2 are necessary. Although (5) is well established for TBW esimtations [3], there is no established coefficient set a_i, $i = 0, \dots, 4$. This is because the coefficients also depend on the measurement protocol of the BIA device, e.g., on the position of the electrodes. As we are not aware of any published coefficient set for our BIA device, the coefficients were estimated in a preprocessing step. This was performed with ordinary least squares regression (OLS, [13]) of (5), adapted to our situation of only male subjects:

$$V_{ij}^{\text{BIA}} = a_0 + a_1 \frac{H_j^2}{|Z_{ij}|} + a_2 W_{ij} + a_3 A_j. \tag{13}$$

In this equation, V_{ij}^{BIA} denotes the absolute TBW computed by the BIA device, Z_{ij} the bioimpedance measured by the BIA device, W_{ij} the weight measured by the BIA device, A_j and H_j the subject's age and height, respectively. On basis of these measurements of all five subjects, the coefficient set was estimated using the OLS implementation of MATLAB (The MathWorks, Natick, MA, USA).

Having the coefficients a_1 and a_2, the function f was learned with two different approaches: a linear approach and a nonlinear approach. The linear approach was OLS, using the implementation of MATLAB.

The nonlinear approach was ϵ-support vector regression (ϵ-SVR, [14]) with a Gaussian radial basis function (RBF) kernel, using the implementation of the LIBSVM [15]. For ϵ-SVR, all measurements were first normalized to the interval $[0; 1]$ as recommended in the LIBSVM documentation. The results of the regression were afterwards rescaled to the original range.

This ϵ-SVR configuration requires three parameters. First, the parameter ϵ that determines the maximal deviation of function values $f(\vec{T}_{ij})$ from reference values e_{ij}, which is not yet penalized. This parameter was fixed to $\epsilon = 0.01$. Since the values were normalized to the interval $[0; 1]$, this corresponded to a maximal, non-penalized deviation of 1% of the total value range. Second, the parameter C that determines the trade-off between generalization and overfitting. Third, the parameter γ of the Gaussian RBF kernel that determines the width of the kernel. The two parameters C and γ were determined with a grid search in $\{10^n\}_{n=-3,-2,\ldots,3}$. In brief, the grid search evaluated every pair of parameters C and γ in a leave-one-subject-out cross-validation (LOSO-CV, [13]). The LOSO-CV computed the residual sum of squares (RSS, [13]) of the j-th test subject

$$\mathrm{RSS}_f(j) = \sum_{i=0}^{8} (f(\vec{T}_{ij}) - e_{ij})^2 \tag{14}$$

where the function f was learned on the remaining training subjects. Note that RSS was selected because the linear approach OLS also minimizes this criterion [13]. After every subject has once been labeled as test subject, the LOSO-CV returned the average RSS over all test subjects

$$\overline{\mathrm{RSS}}_f = \frac{1}{5} \sum_{k=1}^{5} \mathrm{RSS}_f(j_k). \tag{15}$$

Finally, the grid search returned the pair of parameters C and γ that minimized $\overline{\mathrm{RSS}}_f$. Then, the ϵ-SVR was trained with these parameters again, however, this time, using all five subjects.

In summary, the entire two-stage regression g estimates TBW loss by combining the function f and (8):

$$g(Z_{ij}, W_{ij}, \vec{T}_{ij}) = a_1 H_j^2 \left(\frac{1}{|Z_{0j}|} - \frac{1}{|Z_{ij}| + f(\vec{T}_{ij})} \right) + a_2 (W_{0j} - W_{ij}). \tag{16}$$

Compared to the BIA device (7), only additional information of temperature $\vec{T}_{ij}$ is necessary, once the function g has been initialized with the subject's height H_j, baseline bioimpedance Z_{0j}, and baseline weight W_{0j}.

2) Evaluation Procedure: The entire two-stage regression was also evaluated with a LOSO-CV. The data of every subject j, $j = 1, \ldots, 6$, were once labeled as testing data. The data of the remaining subjects $\{j' | 1 \leq j' \leq 6 \wedge j' \neq j\}$ were labeled as training data $\{j_1, \ldots, j_5\}$. Then, the two-stage regression was trained six times on the training data and evaluated six times on the testing data. In every test run, the LOSO-CV computed the RSS of test subject j

$$\mathrm{RSS}_g(j) = \sum_{i=0}^{8} (\Delta V_{ij}^{\mathrm{TBW}} - g(Z_{ij}, W_{ij}, \vec{T}_{ij}))^2 \tag{17}$$

where the two-stage regression g was learned on the training subjects $\{j_1, \ldots, j_5\}$ (Sec. II-C1). After every subject has once been labeled as test subject, the LOSO-CV computed the average RSS over all test subjects

$$\overline{\mathrm{RSS}}_g = \frac{1}{6} \sum_{j=1}^{6} \mathrm{RSS}_g(j) \tag{18}$$

and the corresponding standard deviation.

To enable comparisons with the BIA device, the same criterions were computed for the TBW loss predicted by the BIA device $\Delta V_{ij}^{\mathrm{BIA}}$:

$$\mathrm{RSS}_{\mathrm{BIA}}(j) = \sum_{i=0}^{8} (\Delta V_{ij}^{\mathrm{TBW}} - \Delta V_{ij}^{\mathrm{BIA}})^2, \tag{19}$$

$$\overline{\mathrm{RSS}}_{\mathrm{BIA}} = \frac{1}{6} \sum_{j=1}^{6} \mathrm{RSS}_{\mathrm{BIA}}(j), \tag{20}$$

and the corresponding standard deviation.

TABLE I. TBW LOSS ESTIMATED BY THE TWO-STAGE REGRESSION AND TBW LOSS ESTIMATED BY THE BIA DEVICE.

Subject	OLS	ϵ-SVR	BIA device
1	7.30	5.74	14.87
2	3.06	5.21	26.44
3	25.88	33.75	30.51
4	0.70	0.74	48.63
5	4.22	5.80	6.03
6	23.52	19.96	15.63
mean ± std	10.78 ± 11.01	11.87 ± 12.54	23.69 ± 15.04

The first column denotes the subject, including mean and standard deviation over all subjects. The second column shows the residual sum of squares (RSS) using ordinary least squares regression (OLS) in the first regression stage. The third column shows the RSS using ϵ-support vector regression (ϵ-SVR) in the first regression stage. The fourth column shows the RSS for the estimations of the BIA device.

III. Results

Tab. I depicts all individual RSS as well as the mean and standard deviation over all individual RSS. The two-stage regression achieved a considerable lower mean RSS than the BIA device. Considering subjects $j = 1, 2, 4, 5$ individually, the two-stage regression also achieved a lower RSS than the BIA device. For subject $j = 3$, the two-stage regression could not considerably reduce the RSS compared to the BIA device. For subject $j = 6$, the two-stage regression could not improve the RSS.

Fig. 1 depicts TBW loss averaged over all test subjects. There are three remarkable observations. First, the BIA device estimated a slight increase of TBW at the beginning ($i = 1, 2$) followed by a slight decrease of TBW ($i = 3, \ldots, 8$). Second, the two-stage regression failed to recognize zero TBW loss at the baseline measurement ($i = 0$). Third, the two-stage regression using ϵ-SVR consistently underestimated TBW loss at the measurements $i = 3, \ldots, 8$.

IV. Discussion

In order to estimate TBW loss during sports, the proposed two-stage regression additionally employed information of skin and core temperature besides bioimpedance. This method considerably reduced the mean RSS compared to the BIA device, which did not include temperature information.

However, the subjects' individual RSS were still quite high. We assume that these individual RSS can be further reduced when the ongoing study will be completed so that data of more subjects will be available. This assumption is supported by the averaged predictions of TBW loss (Fig. 1). In this case, the two-stage regression only slightly deviated from the real TBW loss.

For subjects $j = 3$ and $j = 6$, the two-stage regression could not reduce the RSS as much as for the remaining

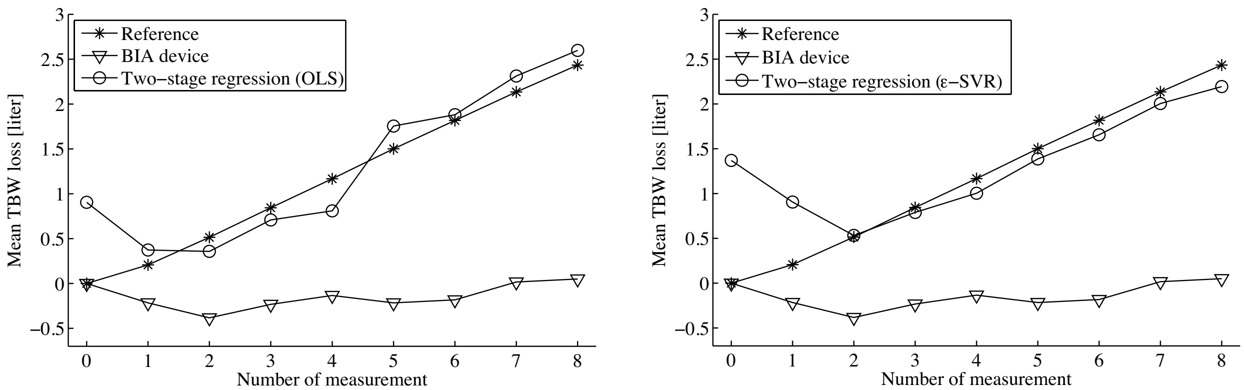

Fig. 1. The estimation of TBW loss is depicted by averaging over all test subjects. On both sides, the proposed two-stage regression is compared to the real TBW loss and to the TBW loss predicted by the BIA device. On the left side, the estimations of the two-stage regression are depicted when ordinary least squares regression (OLS) is used in the first regression stage. On the right side, the estimations of the two-stage regression are depicted when ϵ-support vector regression (ϵ-SVR) is used in the first regression stage.

subjects. A possible explanation might be the natural variation of body temperature among individuals. Therefore, we will examine in future work if relative temperature values can improve the results, instead of absolute values as in the current approach.

Furthermore, it is not crucial that the two-stage regression failed to recognize zero TBW loss at the baseline measurement (Fig. 1). BIA devices are well established for the situation when temperature is not increased. It is not necessary to employ the proposed two-stage regression in such situations. Nevertheless, an explanation might be that there is much less training data for the situation of normal temperature (one measurement per subject) than for the situation of increased temperature (eight measurements per subject).

It is also worth to note the effects of the two conflicting factors, temperature and TBW loss, that influence bioimpedance. The effects can be observed in the averaged TBW loss that was predicted by the BIA device (Fig. 1). In the beginning, the effect of increased temperature seemed to be more intense than TBW loss. The BIA device estimated an increase of TBW because the temperature caused the bioimpedance to decrease. As the subjects lost more water, the effect of TBW loss seemed to be slightly more intense than the increased temperature. The BIA device estimated a slight decrease of TBW.

Finally, it is interesting that ϵ-SVR almost consistently underestimated TBW loss. Although this was not observed for OLS and it could be due to the small number of subjects, it might also indicate a systematic error in the proposed method. The systematic error might be the assumption that temperature information is sufficient to correct the bioimpedance. However, there are more factors that influence bioimpedance [16]. During sports, for example, skin blood flow is also increased, blood vessels are widened, and muscle tissue is warmed up. All these factors should also decrease bioimpedance. On the one hand, these factors should correlate with skin and core temperature to some extent. On the other hand, if the consistent underestimation is still present when the data of all subjects are available, it might indicate that temperature alone cannot conceive all effects. Then, it would be interesting to collect these measurements, e.g., skin blood flow using laser doppler flowmetry, in a further study, and to analyze the ability to predict TBW loss using pattern recognition methods.

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