ORIGINAL PAPER

Effect of regional muscle damage and inflammation following eccentric exercise on electrical resistance and the body composition assessment using bioimpedance spectroscopy

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Abstract
We investigated the effect of muscle damage and inflammation on electrical resistance and the body composition assessment by using bioimpedance spectroscopy (BIS). Twenty-two subjects completed 30 repetitions of maximal eccentric contractions of the elbow flexors with one arm. Whole-body resistance of extracellular and intracellular components (R_e and R_i, respectively) on the exercised and non-exercised sides were measured using BIS. Body composition was calculated from both sides of resistance at baseline and 96 h after exercise. R_e decreased only on the exercised side at 96 h after exercise ($P < 0.05$). Fat-free and fat mass values estimated from resistance on the exercised side were altered by 3.1% and -15.6%, respectively, at 96 h after exercise ($P < 0.05$); those estimated from the non-exercised side were unaltered. Eccentric exercise-induced muscle damage and inflammation reduce R_e and induce non-negligible estimation error in the body composition assessment using BIS.

Keywords Electrical resistance · Muscle damage · Inflammation · Body composition

Introduction

Bioimpedance spectroscopy (BIS) is an accessible method for estimating body composition [i.e., fat mass (FM), fat-free mass (FFM), and body water content]. BIS impresses multi-frequency current to the whole body or each body segment, and body composition was estimated using theoretical and/or empirical estimation equation with measured electrical properties, for instance, reactance (X_c), resistance (R), and impedance (Z). Previous studies have shown a relatively wide limit of agreement between body composition measured by BIS and dual-energy X-ray absorptiometry; however, estimated values were highly correlated and the mean of difference between methods is small in healthy pediatric, adult, and elderly subjects [1–3]. In a study of athletes, BIS was reported to have good accuracy for estimating body water content compared with the isotope dilution method [4]. Additionally, another study suggested that body composition was accurately estimated in trained Caucasians when air-displacement plethysmography and BIS were concomitantly used [5]. Therefore, there is still room for improvement in the accuracy for individual use [6], but some evidence supports the use of BIS in body composition analysis of athletes.

Notably, athletes regularly have exercise-induced inflammation in any body segment and/or their whole body during daily training. Physiological responses to eccentric exercise-induced muscle damage and inflammation are typified by a decrease in maximal voluntary torque and range of motion [7], presence of muscle soreness [7, 8], and an increase in blood concentrations of muscle proteins and inflammatory markers [8–10]. Regional swelling and an increase in the muscle cross-sectional area have been also reported based on magnetic resonance imaging (MRI) and a measurement of the transverse relaxation time [11].

A change in the regional hydration status accompanied by regional muscle damage and inflammation may cause a large estimation error because the equation for estimating body

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composition using BIS generally applies to the assumption that hydration status is constant (i.e., water volume/FFM of approximately 0.73) and uniform between each body segment. A previous study using MRI and single-frequency bioimpedance analysis showed that the electrical properties (e.g., resistance and reactance) of the injured muscle were altered after muscle injury, which was categorized as grades I–III [12, 13], but change in whole-body resistance and the effect on body composition estimation were not revealed. To estimate body composition in athletes accurately, it is important to understand how regional muscle damage and inflammation affect body composition estimation using BIS.

The main objective of this research was to determine the effect of muscle damage following eccentric exercise of the elbow flexors on body electrical resistance and the body composition estimation using BIS. We hypothesized that muscle damage following eccentric exercise would regiospecifically decrease extracellular resistance because of swelling. In addition, a regiospecific increase in body water would cause overestimation of FFM when using a whole-body model of BIS.

Methods

Subjects

Twenty-two male subjects (age, 28.8 ± 3.7 years; height, 172.0 ± 5.1 cm; body mass, 68.8 ± 10.3 kg; body mass index, 23.3 ± 3.6 kg/m^2) participated in this study. Written informed consent was obtained from all participants, and the study procedure was approved by the ethical committee of the Japan Institute of Sports Sciences.

Experimental procedures

Subjects completed the elbow flexion eccentric exercise using one arm in accordance with a previous study [14]. They occasionally participated in recreational sports (e.g., running, cycling, resistance training, and soccer), but did not perform regular training. The exercised arm was determined randomly without reference to the dominant side. According to the manufacturer's guidelines, Biodex system (System 4; Biodex Medical System, New York City, NY, USA) was used for exercise following calibration. Participants were strapped to a dynamometer chair with their arm resting on the armrest. The fully extended elbow joint angle was determined as 0°, and range of motion was set from 130° to 10°. Following familiarization sessions, participants performed 30 repetitions of maximal eccentric exercise of the elbow flexors at 120°/s with a rest period of 12 s between contractions. Participants were instructed to complete each exercise with full effort.

Body resistance, body composition, arm circumference, and blood samples were obtained immediately before exercise and at 24, 48, 72, and 96 h after exercise (days 0, 1, 2, 3, and 4, respectively). Participants were instructed to maintain a normal dietary habit. Vigorous exercise and consumption of an alcoholic drink were restricted during the experiment.

Bioimpedance spectroscopy measurement

Body composition was measured using the BIS system (SFB7; ImpediMed, Pinkenba, QLD, Australia). Electrodes (Red Dot; 3M Health Care, St. Paul, MN, USA) were placed bilaterally on the exercised and non-exercised sides as injection and sensing electrodes. Injection electrodes were placed on the dorsal surface of the hands and feet proximal to the metacarpal–phalangeal and metatarsal–phalangeal joints. Sensing electrodes were placed on the middorsum of the wrist, centered on a line joining the bony prominences of the radius and ulna; the lateral epicondyle of the humerus; tip of the acromion; greater trochanter of the femur, and midanterior ankle, centered on a line joining the malleolus lateralis and malleolus medialis of the upper limb, trunk, and lower limb. The electrode position was marked and standardized for each measurement. Body resistance was measured for the exercised and non-exercised sides of the body for the whole body (wrist-to-ankle model) and the forearm, upper arm, trunk, and leg segments. Measurements were conducted with participants in the standing position while in a temperature-controlled room (21–22 °C).

Resistance values of extracellular and intracellular components (R_e and R_i, respectively) were based on a Cole plot using ImpediMed SFB7 Multi-Frequency Analysis software (ImpediMed, Pinkenba). The analytical setting was set up in accordance with that in previous studies [15, 16]. In the whole-body model of BIS, FM, FFM, extracellular and intracellular water (ECW and ICW, respectively) content, and total body water (TBW) content were calculated from wrist-to-ankle resistance using a manufacturer-provided equation based on the Hanai mixture theory [17, 18]. In the segmental model, the impedance index of the extracellular (L^2/R_e) and intracellular (L^2/R_i) components was calculated as relative indicators of ECW and ICW contents, where L is the length (cm) of each segment.

Upper arm circumference

The upper arm circumference was measured using an MRI system (Magnetom Skyra, Verio; Siemens, Erlangen, Germany). Cross-sectional images of the area 60% distal to the length between the acromial process and epicondylus lateralis humeri were obtained using a body array and spine array coil. An area-measuring program (ISIS, Hitachi

Medical Corporation, Tokyo, Japan) was used to determine circumference.

Blood analysis

Blood samples were taken from the antecubital vein using vacuum tubes. Samples were centrifuged at $3000 \times g$ for 10 min and stored at 4 °C until analysis. Serum creatine kinase (CK) was measured in an independent laboratory (LSI Medience Corporation, Tokyo, Japan).

Statistical analysis

All data are presented as a mean ± standard deviation. Data of the serum CK on day 1 and arm circumference were obtained from 21 and 16 participants, respectively, in whom they could be measured. Two-factor factorial repeated-measure analysis of variance (ANOVA) was used to detect differences in data between the exercised and non-exercised sides. One-way repeated-measure ANOVA was used to detect changes in the serum CK level and upper arm circumference. When a significant interaction was identified, data were subsequently analyzed using the Bonferroni post hoc test. Statistical significance was set at $P < 0.05$. Statistical calculations were performed using SPSS Statistics version 24 (IBM Corp., Armonk, NY, USA).

Results

Serum creatine kinase level

Serum CK levels increased with each day after exercise (main effect for time $P < 0.001$). Serum CK levels at day 1 and day 2 were not significantly different compared with those on day 0 (day 0: 185 ± 267, day 1: 2152 ± 4392, and day 2: $6563 \pm 11\,892$ IU/L). However, serum CK levels on day 3 and day 4 were significantly increased compared with the baseline value (day 3: $13\,495 \pm 15\,588$ and day 4: $16\,475 \pm 14\,850$ IU/L; both $P < 0.01$ vs day 0).

Upper arm circumference

Upper arm circumference of the exercised side was 26.3 ± 2.4 cm on day 0. It continued to increase after exercise compared to the baseline value (day 1: 26.9 ± 2.2, day 2: 27.0 ± 2.2, day 3: 27.5 ± 2.1, and day 4: 27.7 ± 2.2 cm; main effect for time $P < 0.001$, all $P < 0.05$ vs day 0).

Segmental resistance and water status

On day 0, L^2/R_e and L^2/R_i in the forearm, upper arm, trunk, and leg were similar between the exercised and non-exercised sides. The L^2/R_e in the forearm and upper arm increased in the exercised side with each day after exercise and was higher than that in the non-exercised side (Fig. 1).
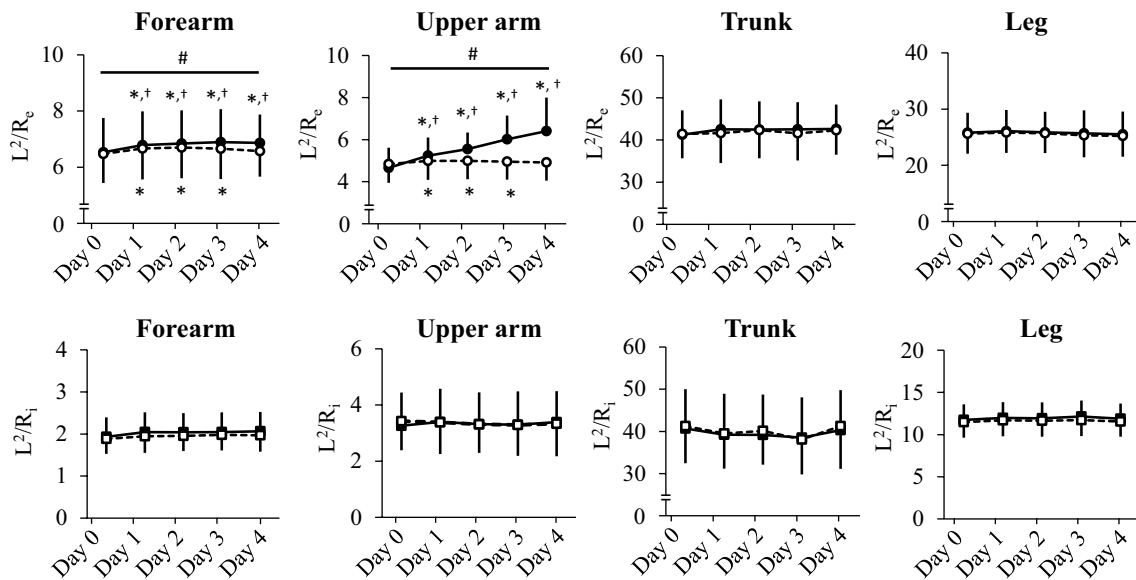

Fig. 1 Changes in impedance indexes in each segment. Values are presented as mean ± standard deviation. Open circles or square with dotted line, non-exercised side; dark circles or square with solid line, exercised side. #$P < 0.05$, interaction for time and condition.

*$P < 0.05$, from day 0 in the same condition. †$P < 0.05$, between conditions at the same time. L^2/R_e impedance index of the extracellular components, L^2/R_i impedance index of the intracellular components

Segmental resistance values and impedance indexes at day 0 and day 4 are shown in Table 1. Significant correlations were found between percent changes from day 0 to day 4 of the L^2/R_e in the upper arm and serum CK level, and L^2/R_e and upper arm circumference (Fig. 2a, b).

Wrist-to-ankle resistance and whole-body composition

Wrist-to-ankle R_e and R_i were similar between the non-exercised and exercised sides of the body on day 0 (non-exercised side 578 ± 68 and 1194 ± 226; exercised side 582 ± 74 and 1195 ± 253, respectively). There was a significant interaction for time and condition for wrist-to-ankle R_e ($P < 0.001$). In the exercised side, wrist-to-ankle R_e decreased with each day after exercise (day 1, 556 ± 67; day 2, 550 ± 62; day 3, 544 ± 64; day 4, 540 ± 59; all $P < 0.05$ vs day 0). In the non-exercised side, wrist-to-ankle R_e decreased at day 1 (568 ± 66; $P = 0.044$), but those at days 2, 3, and 4 were similar to day 0 (566 ± 65, 574 ± 69, 575 ± 63, respectively; all $P > 0.05$). Wrist-to-ankle R_i was not changed in the non-exercised and exercised sides (interaction for time and condition, $P = 0.148$; main effect for time, $P = 0.354$; main effect for condition, $P = 0.504$). Whole-body compositions estimated from the wrist-to-ankle resistance of the non-exercised and exercised sides at day 0 and day 4 are shown in Table 2. On day 0, body composition parameters estimated from the non-exercised and exercised sides of the body were similar. At day 4, FFM, ECW, ICW, and TBW values estimated from the exercised side were larger, and FM estimated from the exercised side was smaller than that estimated from the non-exercised side (interaction for time and condition, both $P < 0.05$). There was no change in body mass from day 0 to day 4 (68.8 ± 10.3 to 68.9 ± 10.2 kg; main effect for time $P = 0.425$).

Discussion

In this study, we demonstrated the effect of eccentric exercise-induced regional muscle damage and inflammation on body resistance and body composition analysis using BIS. Our results clearly showed that extracellular resistance of the arm decreased after eccentric exercise of the elbow flexors in one arm. Consequently, FFM and FM values estimated from the non-exercised and exercised sides using BIS varied widely. Hence, our hypotheses are verified by our findings.

Table 1 Non-exercised and exercised side of body resistance and impedance index in each segment

	Non-exercised side		Exercised side		Interaction
	Day 0	Day 4	Day 0	Day 4	P value
Forearm					
R_e (Ω)	156 ± 20	153 ± 17	156 ± 23	147 ± 17*,†	0.004
R_i (Ω)	541 ± 96	519 ± 96	542 ± 130	502 ± 103	0.207
L^2/R_e	6.48 ± 1.04	6.57 ± 0.91	6.53 ± 1.22	6.87 ± 1.01*,†	0.006
L^2/R_i	1.89 ± 0.36	1.97 ± 0.39	1.93 ± 0.47	2.06 ± 0.46	0.405
Upper arm					
R_e (Ω)	120 ± 19	118 ± 18	124 ± 22	91 ± 17*,†	< 0.001
R_i (Ω)	181 ± 56	186 ± 57	188 ± 61	187 ± 72	0.120
L^2/R_e	4.84 ± 0.90	4.91 ± 0.86	4.66 ± 0.96	6.40 ± 1.59*,†	< 0.001
L^2/R_i	3.43 ± 1.18	3.34 ± 1.10	3.27 ± 1.04	3.39 ± 1.16	0.145
Trunk					
R_e (Ω)	68 ± 8	66 ± 7	68 ± 8	66 ± 7	0.582
R_i (Ω)	70 ± 15	70 ± 15	73 ± 24	73 ± 18	0.919
L^2/R_e	41.44 ± 6.03	42.30 ± 5.54	41.23 ± 5.79	42.64 ± 5.76	0.305
L^2/R_i	41.24 ± 8.81	41.27 ± 10.15	40.67 ± 9.35	40.30 ± 9.50	0.883
Leg					
R_e (Ω)	234 ± 26	238 ± 28	233 ± 28	237 ± 30	0.373
R_i (Ω)	529 ± 98	525 ± 93	521 ± 105	515 ± 101	0.502
L^2/R_e	25.62 ± 3.54	25.23 ± 3.68	25.81 ± 3.55	25.54 ± 4.01	0.466
L^2/R_i	11.49 ± 1.85	11.55 ± 1.80	11.75 ± 2.14	11.88 ± 2.09	0.496

Values are presented as mean $\pm$ standard deviation. *$P < 0.05$, from day 0 in the same condition. †$P < 0.05$, between conditions at the same time

R_e resistance of extracellular components, R_i resistance of intracellular components, L^2/R_e impedance index of the extracellular components, L^2/R_i impedance index of the intracellular components
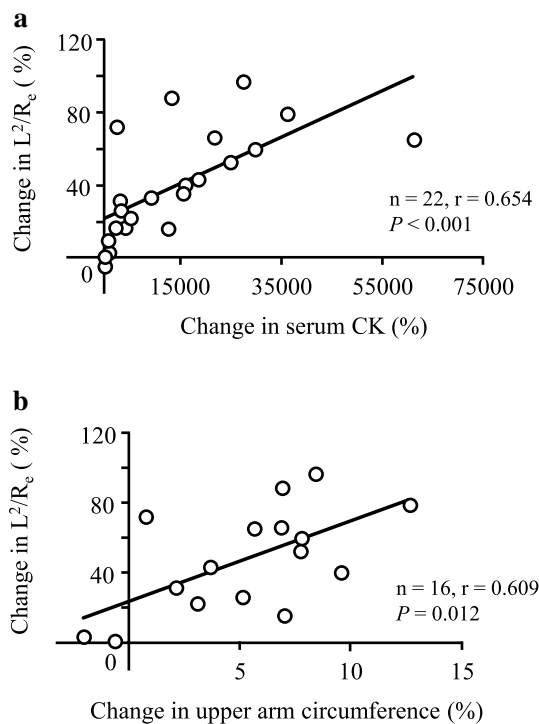
Fig. 2 Relationship between the **a** extracellular impedance index (L^2/R_e) and serum creatine kinase (CK) level, and **b** L^2/R_e and upper arm circumference of the upper arm on the exercised side

Regional muscle damage was induced by eccentric exercise of the elbow flexors in this study, and the serum CK level obviously increased 3 days after exercise. This finding agrees with the results of previous studies in which a similar muscle damage model was used [7, 19]. Technically, it is difficult to determine the site of original inflammation; however, this response probably originated from the segment that underwent eccentric exercise since participants were prohibited from performing any exercise, except for daily activity during the intervention period.

Our data showed that change in resistance occurs regio-specifically and is attributed to extracellular components in a multi-segment model of BIS. These results were complementary to those reported in a previous study [12, 13]; the authors reported change in resistance at 50 kHz of current, which is reflected by both intracellular and extracellular resistances, only in the injured segment. One possible cause of the induced change in R_e is swelling. Following muscle damage, vasodilatation and increased permeability of the blood vessels occurs because of the effects of some substrates (e.g., histamine and kinin); as a result, swelling is induced in the damaged site [20, 21]. Principally, in BIS, an increase in tissue water content is linked to a decrease in resistance, and water flux with swelling appears likely to be reflected by R_e [22]. The suggestion that swelling is an inflammatory response that causes a decrease in resistance is partly supported by our results that change in the impedance index of the extracellular component correlates with change in the serum CK level and upper arm circumference, which are main indicators of inflammation and swelling.

Four days after the eccentric exercise, FFM and FM estimated from the wrist-to-ankle resistance of the exercised side were found to have changed by approximately 1.8 kg (Table 2). This assessment must include some errors because the study period was too short for body composition to be altered. In addition, our results showed that body composition estimated from the non-exercised side and body weight remained static. The segment model of BIS suggested that only about 100 mL of ECW was accumulated in the exercised arm in that the ECW content could be estimated by multiplying L^2/R_e by the assumed rho value, which is generally 47 for men [23, 24]. A previous study demonstrated that the total body resistance values were 52% for the arm (34% for the forearm and 18% for the upper arm), 4% for the trunk, and 44% for the leg of Caucasian adults [25]. Similarly, our data of Japanese young adults showed that arm resistance was more than 40% of the total body resistance. Accordingly, it can be interpreted that a decrease in arm resistance is caused by a small absolute amount of water accumulation after eccentric exercise, however it is excessively reflected by an increase in FFM (and compensatory decrease in FM) in the whole-body model due to the characteristic of resistance distribution and assumption about hydration of FFM.

Table 2 Whole-body composition estimated from the wrist-to-ankle resistance of the non-exercised and exercised sides

	Non-exercised side			Exercised side			Interaction
	Day 0	Day 4		Day 0	Day 4		P-value
Fat-free mass (kg)	57.8 ± 8.7	58.0 ± 8.5	(− 0.3)	57.8 ± 8.8	59.6 ± 8.2*,†	(3.1)	< 0.001
Fat mass (kg)	11.0 ± 4.1	10.9 ± 4.0	(− 0.7)	11.0 ± 4.4	9.3 ± 4.7*,†	(− 15.6)	< 0.001
ECW (L)	18.2 ± 2.6	18.2 ± 2.5	(0.2)	18.1 ± 2.7	19.0 ± 2.4*,†	(4.7)	< 0.001
ICW (L)	24.2 ± 3.9	24.2 ± 3.9	(0.4)	24.2 ± 3.9	24.6 ± 3.7*	(2.0)	0.011
TBW (L)	42.3 ± 6.4	42.5 ± 6.2	(0.3)	42.3 ± 6.4	43.6 ± 6.0*,†	(3.1)	< 0.001

Values are presented as mean ± standard deviation. The average rate of change (%) is noted in brackets.
*$P < 0.05$, from day 0 in the same condition. †$P < 0.05$, between conditions at the same time

ECW extracellular water, *ICW* intracellular water, *TBW* total body water

For athletes, the fact that regional exercise-induced muscle damage and inflammation impair body composition estimation using BIS deserves more attention since these individuals are prone to experiencing muscle damage in daily training. Our data strongly suggest that the current-carrying area should be determined to exclude damaged segments.

There are some limitations in this study. First, BIS can measure R_e and R_i separately because the cell membrane acts as a capacitor. However, since the muscle cells may have structural damage after eccentric exercise [26], it is unclear whether cellular resistance is correctly discriminated. If the cell membrane does not act as a capacitor, an increase in R_e and a compensatory decrease in R_i coinstantaneously occur in principle. However, the exercise side-specific behavior of R_i was not observed in this study. Second, we used an equation based on the Hanai mixture theory and Cole plot to estimate body composition. Because assumed rho values were applied in the estimation equation we used here, if structural characteristics of body water (i.e., "free water" or "bond water" [27]) were altered with muscle damage and inflammation, body composition calculation includes additional errors. In addition, several other estimation equations have been proposed in previous studies [28]. It should be understood that the effect of muscle damage and inflammation on the body composition analysis depends on the applied estimation equation. Third, because of body resistance distribution, we interpreted that each body segment should have a different effect on muscle damage-induced change of resistance in the body composition assessment. Similarly, the effect on body composition analysis depends on whether muscle damage and inflammation occur in the dominant or non-dominant side in that body resistance at the dominant side differs from that in the non-dominant side [29]. To assess the body composition accurately using BIS, future study to confirm the above problems should be conducted gradually.

Conclusions

Muscle damage and inflammation following eccentric exercise of the elbow flexors induce regiospecific reduction in extracellular resistance. Because of resistance distribution in the body, even if muscle damage occurs in a small segment of the body, non-negligible estimation error is caused in the body composition assessment when using a whole-body model of BIS.

Compliance with ethical standards

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