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Time-course bicep tissue bio-impedance changes throughout a fatiguing exercise protocol

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ABSTRACT

This study investigated the localized electrical-impedance changes in the biceps tissues throughout a fatiguing exercise protocol. During the protocol, 17 subjects performed 10 sets of bicep curl repetitions at either 60% or 75% of their one-repetition maximum weight until task failure. The localized tissue impedance (resistance, reactance, phase angle) was measured at 10 kHz, 50 kHz, and 100 kHz immediately after each of 10 sets for comparison against the baseline pre-fatigue measures. A trend of decreasing resistance and reactance magnitude were observed, with greater changes occurring as the protocol progressed. Statistical testing demonstrated statistically significant changes in resistance, reactance, and phase angle for both groups of participants. The significant changes in resistance were observed at earlier time-points than the reactance and phase angle changes for both groups.

1. Introduction

Participation in exercise and training programs is widely employed to enhance fitness, strength, endurance, and mobility. These outcomes are important for multiple populations including athletes aiming to improve their performance in competition and older adults aiming to maintain their independence and quality of life. Regardless of the population, during high-training loads skeletal muscle experiences the effects of repetitive contractions which include sarcomere damage [1], shortened connective tissue, passive muscle stiffness, and decreased range of motion (ROM) [2,3]. An increase in muscle edema paired with a decrease in muscle quality has been hypothesized as the reason for decreased muscular strength following exercise [2]. Each of these changes (sarcomere damage, shortened connective tissue, edema, swelling) alter the skeletal muscle. While changes in skeletal muscle can be quantified using direct methods such as muscle biopsies or magnetic resonance imaging (MRI) and indirect methods such as force loss, the levels of muscle proteins in the blood, and self-reported muscle soreness [4]; the challenge with all of these methods are that they are resource-intensive (in terms of costs and required equipment), invasive (in the case of biopsies and blood draws), and are not able to monitor skeletal muscle in real time or during free-living activities. This warrants the continued investigation of methods to quantify changes in skeletal muscle during activity.

Electrical impedance myography (EIM), also referred to as bioimpedance measurements, is being actively investigated as a method to quantify the passive electrical behavior of tissue. EIM quantifies the resistance of a material to an injected electrical stimulus and have been used to detect physiological changes in biological tissues [5,6]. The passive electrical behavior of a biological tissue is dependent on the cell population, cell volumes, cellular membrane integrity, and the intra / extra cellular fluids. EIM provides information on the underlying tissue, structure and fluids, which is hypothesized to be able to detect the metabolic changes / damage that is occurring due to repeated contractions during activities that lead to fatigue.

EIM have been widely used for body composition analysis [7] and have recently been investigated to monitor muscle activity in lower-limb amputees [8], to assess soft tissue damage in professional athletes [9], assessing knee osteoarthritis [10], and monitor hydration in dialysis patients [11,12]. Currently, the most active area of research regarding the electrical impedance properties of skeletal muscle investigates its application as a clinical diagnostic tool to assess neuromuscular disorders [6,13–15]. EIM has been investigated for neuromuscular applications related to ALS, spinal muscular atrophy, nerve injury and radiculopathy, carpal tunnel syndrome, Duchenne muscular dystrophy, facioscapulohumeral muscular dystrophy, inflammatory myopathies, sarcopenia, and disuse atrophy [14]; highlighting the significant clinical potential of this technique for monitoring and diagnosis. EIM is also being investigated to track impaired muscles of neurological injury patients, specifically for evaluating paretic muscle changes after stroke [16,17] and spinal cord injuries [18,19]. The potential for

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EIM to quantify muscle without requiring patient effort makes this a very attractive technique for these applications.

There have recently been a series of EIM studies investigating skeletal muscle for changes as a result of fatigue in human subjects [20–24] and muscle atrophy and injury in mice [26,27]. These studies support that EIM may be a useful technique for quantifying activity-induced changes. Now, while previous studies that induced fatigue in the bicep of participants did show statistically significant differences between the pre/post fatigue electrical impedance [23,24], they did not explore at which interval that statistically significant changes could be observed. Therefore, while these works support that EIM can detect changes between unfatigued and severely fatigued states (with severely fatigued defined here as an inability to complete a task of an additional dumbbell bicep curl repetition), there is limited data on if changes can be detected prior to this exhaustive level of fatigue/task failure. Identifying the points at which changes due to activity-induced fatigue can be detected and relating these to the physiological changes in the tissue are important if EIM is to be clinically significant to quantify the level fatigue, estimate future task performance based on current levels of fatigue, and individually tailor exercise or rehabilitation protocols (in terms of repetitions or rest) to an individuals specific tissue response. This work aims to address this gap by expanding on the analyses presented in [23,24] and identifying at which specific interval that differences in the impedance measures collected from the biceps tissue of participants emerged during a multi-set exercise-protocol targeted to induce significant fatigue.

In this work the resistance, reactance, and phase angle components of the electrical impedance at 10 kHz, 50 kHz, and 100 kHz collected immediately prior to the fatigue protocol and at 10 timepoints throughout the protocol are compared. Each of the 10 timepoints were collected immediately after completion of a set of repetitions until task failure, increasing the level of fatigue after each set. A multi-set protocol was utilized to induce significant fatigue, such that even after a period of rest the participants ability to complete the task was inhibited. Statistically significant differences between the resistance, reactance, and phase angle measures at all frequencies were detected, though the significant differences appeared at later timepoints for the phase angle, than the reactance and resistances for both groups.

2. Methods

2.1. Human sample

This study analyzed measurements collected from the left and right biceps of 17 participants (14 males, 3 females, with an average age of 22.2 ± 3.2 years) immediately prior and throughout the course of a fatiguing exercise protocol. This study was reviewed and approved by the institutional review board of The University of Alabama (16-OR-234). All study participants were recruited from The University of Alabama and were screened prior to participation using a health questionnaire. Those participants who had any reported muscle or joint problems or who had any recent adverse reactions to exercise were excluded. Informed written consent was obtained from each participant prior to their inclusion in the study. Note that that initial pre/post analysis of this dataset described elsewhere ([23,24]) comprised data for 18 participants, but one participant was excluded from this analysis because that participant did not have complete data for the entire protocol.

2.2. Exercise protocol

Each participant executed a fatiguing exercise protocol using dumbbell bicep curls at either 60% ($N = 10$) or 75% ($N = 7$) of their previously assessed one-repetition maximum (1-RM) until task failure. The 1-RM value for each participant is the maximum weight that they were able to successfully lift for the dumbbell bicep curl exercise. The grouping of participants by intensity relative to their 1-RM weight was introduced to control for differences between the relative strengths of each participant, which could have an impact on the exercise induced changes. The weights used by participants in this study ranged from 10 lbs to 55 lbs, with mean $\pm$ standard deviations of 23 ± 3.5 lbs for the left bicep 60% group, 23 ± 3.5 lbs for the right bicep 60% group, 28.1 ± 9.2 lbs for the left bicep 75% group, and 28.8 ± 9.5 lbs for the right bicep 75% group. The selection of 60% and 75% intensities was based on this range being common within resistance training protocols. During this protocol, participants completed repetitions of the exercise until failure (this series of repetitions will be referred to as one set). After a two-minute rest the participants completed an additional set. This process continued until the participants had completed 10 sets at which point the protocol was terminated.

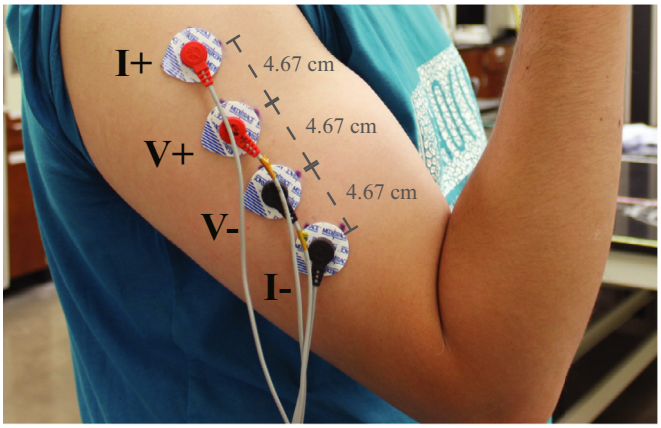

Fig. 1. Electrode configuration placement and separation distances used for data collection.

2.3. Localized electrical impedance measurements

The localized electrical impedance measurements were collected from each participant using a tetrapolar electrode configuration in which two current injection electrodes (**I+, I–**) were placed on the lateralis side of the bicep. After cleaning the skin site with alcohol wipes and letting the site dry, four Ag/AgCl Kendall 133 electrodes (Kendall, Canada) were placed on the biceps. The current injection electrodes were placed 14 cm apart with the voltage sensing electrodes (**V+, V–**) placed 4.67 cm apart. This configuration of electrodes on the bicep of a study participant is detailed in Figure 1. For all collected measurements, participants were in a standing position and asked to relax their muscles with their arms resting naturally at the sides of their body. For the protocol, the left arm was always fatigued before the right bicep for each participant [23]. The intent of this was to identify if there was a difference in the impedance changes when one arm was fatigued before the other, which could indicate global changes occurring in one muscle group as a result of fatigue may impact measurements from another muscle group. It was noted in the statistical analyses of Fu and Freeborn et al.[23] that there were no significant differences in the impedance changes of the left/right arms, supporting that both arms could be monitored independently.

The impedance measures at each timepoint were collected using a Keysight E4990A impedance analyzer (Keysight Technologies, CA) with a custom-interface to adapt the BNC-connectors of the E4990A to a cable-set with the required snap connectors for the Ag/AgCl electrodes. Using this setup, measurements were collected from 10 kHz to 100 kHz at 67 logarithmically spaced frequencies.

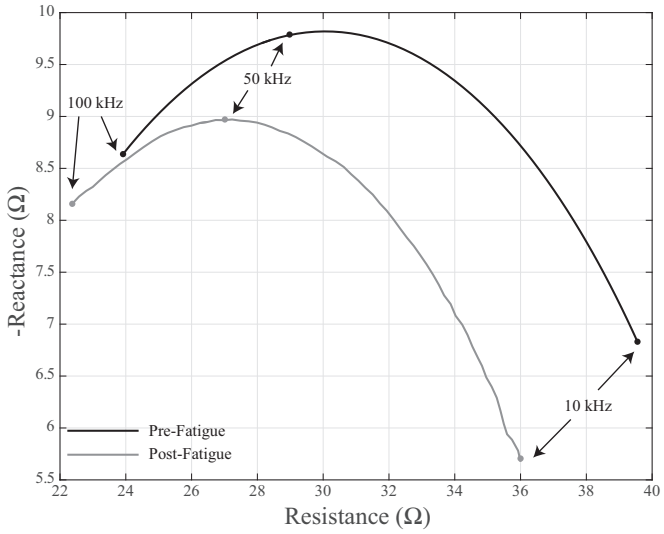

Fig. 2. Pre (black) and post-fatigue (grey) bicep tissue bio-impedance measurements from a single participant after 10 sets of bicep curl repetitions.

This frequency range was selected because it is widely employed in bio-impedance applications [20] and the most appropriate for the E4990A [28]. These measurements were collected using the maximum accuracy setting (MEAS=5) which increases the time to measure each discrete frequency. It should be noted that before data collection, the Keysight E4990A was calibrated using the open/short/load procedure with the developed interface. Further details of this interface and its accuracy evaluation are detailed in [23]. The impedance datasets collected by the Keysight E4990A were imported directly into MATLAB (Mathworks, MA) on an external computer using the instrument Standard Commands for Programmable Instruments (SCPI) syntax with the USB interface. In MATLAB, these data were organized into the resistance, reactance, and phase angle datasets for further analysis. The phase angles (θ) were calculated using the resistance (R) and reactance (X) measurements such that: $\theta = \tan^{-1}(X/R)$.

2.4. Data Analysis

The resistances, reactances, and phase angle at 10 kHz, 50 kHz, and 100 kHz were analyzed and compared between the 60% and 75% groups with the left and right arm data group together. Friedman tests were selected to determine if there were differences in the resistances and reactances during the fatiguing exercise protocol. A non-parametric test was selected for this analysis because all of the resistance and reactance data was not normally distributed as assessed by the Shapiro-Wilk's test. The significance level was determined as $p < 0.05$ for all statistical analyses. Further, pairwise comparisons were performed with a Bonferroni correction for multiple comparisons; comparisons were only made between the pre-fatigue values and measured values after each set of repetitions for a total of 10 comparisons. All statistical analyses in this study were done using SPSS v24 (IBM Inc., WA).

3. Results

To visualize the multi-frequency impedance of a single participant, the pre- and post-fatigue bio-impedance measurements from 10 kHz to 100 kHz are given in Figure 2 as solid black and grey lines, respectively. Both pre and post-fatigue measurements display the arc-behaviour typical of a Cole-impedance, a common electrical equivalent circuit used to fit data of this nature [25]. Notice that the peak of the post-fatigue measures has a lower maximum reactance and that the resistance also decreases (given by a shift of the arc to the left) when compared to the pre-fatigue measures. These changes support that the physiological changes that occur as a result of exercise in the bicep tissue of this participant are reflected in their localized electrical impedance measurements.

To compare the changes that occur in both groups of participants throughout the protocol, the 10 kHz, 50 kHz, and 100 kHz resistance, reactance, and phase angle means were calculated at each timepoint. These 3 frequencies were selected because they represent the maximum (100 kHz), minimum (10 kHz), and mid-point (50 kHz) frequencies of the data collected. The mean resistance, reactance, and phase angle for the 60% 1-RM group are given in Figures 3(a)–(c) with the values for the 75% 1-RM group given in Figures 4(a)–(c). The mean number of executed repetitions in each set of dumbbell bicep curls is given in Figures 3(d) and 4(d), for the 60% and 75% groups, respectively.

Observing the executed repetitions, given in Figures 3(d) and 4(d), the effects of fatigue are noticeable in both groups as a decrease in the mean number of completed repetitions compared to the first set. The exercise-induced fatigue resulted in decreases of 79.3% and 83.3% for the number of completed repetitions by the right and left biceps of the 60% 1-RM group between the first and last set and decreases of 79.6% and 75.6% for the 75% 1-RM group. The most significant between-sets decreases occurs between the first and second sets, with decreases of 45.6% and 48.9% for the right and left biceps of the 60% 1-RM group and 38.7% and 34.4% for the 75% 1-RM group.

A decreasing trend is observed in the mean resistance measurements of both groups in Figures 3(a) and 4(a). For all frequencies the bicep tissue resistance decreases as the number of completed repetitions/sets increases. At 10 kHz, the resistance shows a decrease of 8.2% and 9.3% for the right and left arm of the 60% 1-RM group, respectively, and 7.2% and 8.1% for the right and left arm of the 75% 1-RM group, respectively, comparing timepoint 10 to the pre-fatigue resistance. At 50 kHz, the resistance shows a decrease of 5.6% and 6.6% for the right and left arm of the 60% 1-RM group, respectively, and 5.8% and 6.3% for the right and left arm of the 75% 1-RM group, respectively, again comparing timepoint 10 to the pre-fatigue resistance. Finally, the 100 kHz resistance shows decreases of 5.6% and 5.8% for the right and left arm of the 60% 1-RM group, respectively, and 5.7% and 5.6% for the right and left arm of the 75% 1-RM group, respectively.

Similar trends are observed in the 50 kHz and 100 kHz reactance measurements of both groups in Figures 3(b) and 4(b); with decreases in reactance magnitude observed as the number of completed repetitions/sets of the exercise increases. However, the 10 kHz reactance does not follow this same trend. Instead the 10 kHz data for both 60% and 75% 1-RM groups have an increase in reactance magnitude at set 1 (compared to the pre-fatigue measures), after which the reactance shows the same trends as the other data. The phase angle in Figures 3(c) and 4(c) also display this overall trend.

Based on the Friedman test the resistances, reactances, and phase angles at all frequencies were statistically significantly different ($p < 0.0005$) at the different time points during the fatiguing protocol. The specific Friedman test results for the 60% 1-RM group are: 1) Resistance, 10 kHz, $\chi^2(10) = 142.627$, 2) Resistance, 50 kHz, $\chi^2(10) = 107.182$, 3) Resistance, 100 kHz, $\chi^2(10) = 88.591$ 4) Reactance, 10 kHz, $\chi^2(10) = 168.027$, 5) Reactance, 50 kHz, $\chi^2(10) = 157.264$, 6) Reactance, 100 kHz, $\chi^2(10) = 149.8$, 7) Phase Angle, 10 kHz, $\chi^2(10) = 166.491$, 8) Phase Angle, 50 kHz, $\chi^2(10) = 150.718$, 9) Phase Angle, 100 kHz, $\chi^2(10) = 128.200$. The specific Friedman test results for the 75% 1-RM group are: 10) Resistance, 10 kHz, $\chi^2(10) = 82.277$, 11) Resistance, 50 kHz, $\chi^2(10) = 64.121$, 12) Resistance, 100 kHz, $\chi^2(10) = 65.135$, 13) Reactance, 10 kHz, $\chi^2(10) = 91.76$, 14) Reactance, 50 kHz, $\chi^2(10) = 82.251$, 15) Reactance, 100 kHz, $\chi^2(10) = 69.350$, 16)

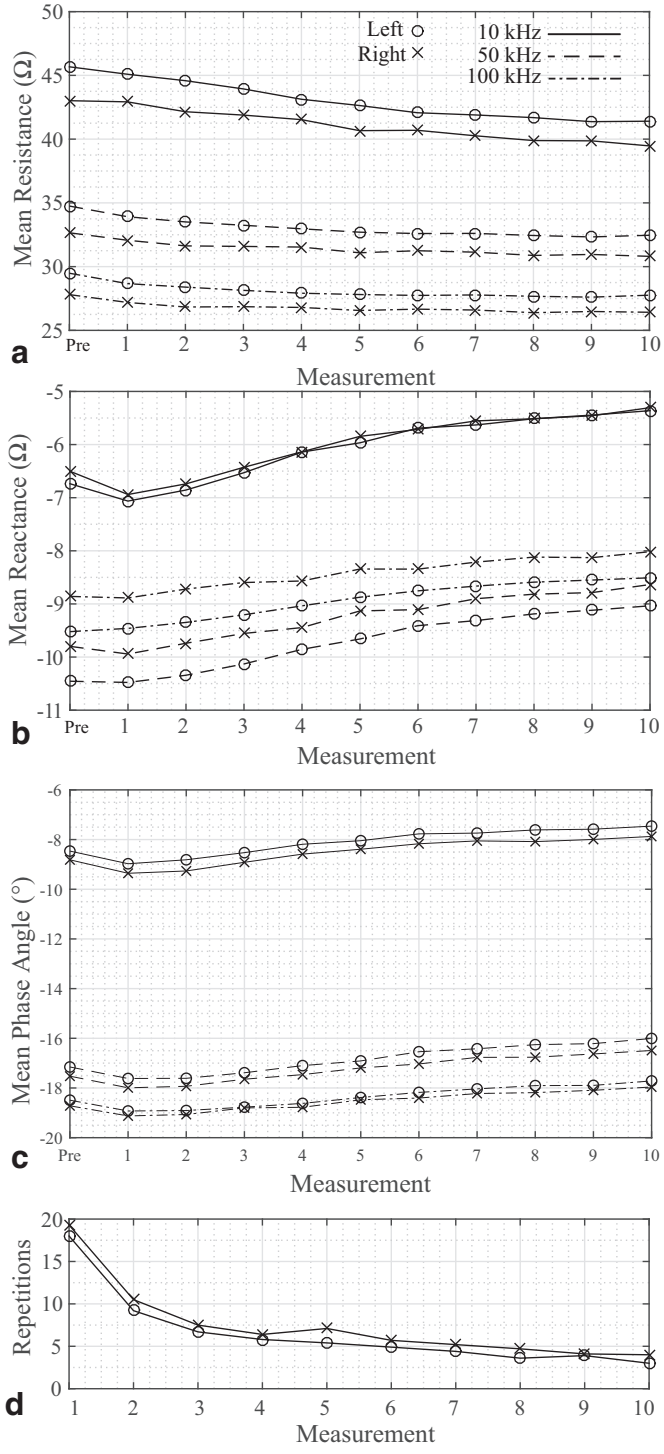

Fig. 3. Mean (a) resistance, (b) reactance, and (c) phase angle of 10 kHz (solid), 50 kHz (dashed), and 100 kHz (dash-dotted) bicep tissue measurements of left (o) and right (x) arms with (d) mean dumbbell bicep curl repetitions from 60% group during fatigue protocol.

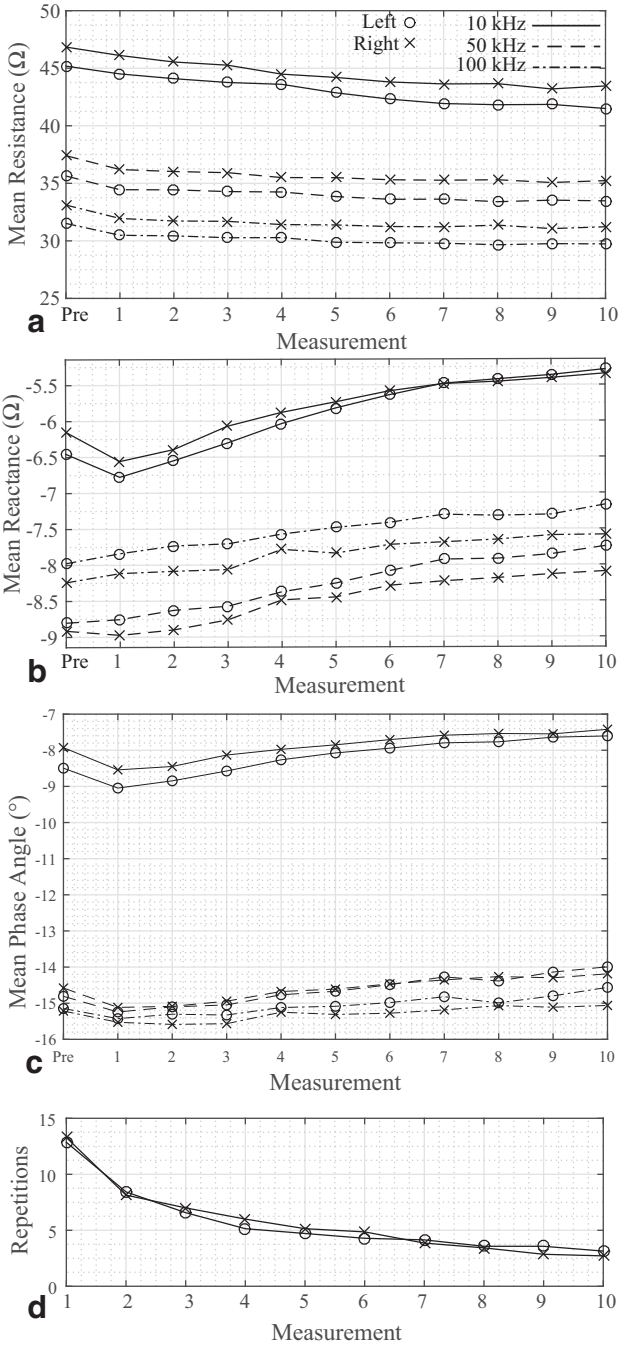

Fig. 4. Mean (a) resistance, (b) reactance, and (c) phase angle of 10 kHz (solid), 50 kHz (dashed), and 100 kHz (dash-dotted) bicep tissue measurements of left (o) and right (x) arms with (d) mean dumbbell bicep curl repetitions from 75% group during fatigue protocol.

Phase Angle, 10 kHz, $\chi^2(10) = 100.458$, 17) Phase Angle, 50 kHz, $\chi^2(10) = 82.764$, 18) Phase Angle, 100 kHz, $\chi^2(10) = 45.427$. The median resistance, reactances, and phase angles used for the Friedman tests at each frequency (10 kHz, 50 kHz, 100 kHz) are given in Table 1, Table 2, and Table 3, respectively. The pairwise comparisons that have a statistically significant difference (compared to the pre-fatigue measure) at the $p < 0.05$ level are denoted in these tables with an asterisk (*).

4. Discussion

The changes of both resistance and reactance in the biceps tissues due to exercise induced fatigue were significant within the 60% and 75% groups, further supporting the results presented previously by Fu and Freeborn [23] that compared the pre-fatigue and post-fatigue (Set 10) measures. From the analysis of the changes throughout the protocol, the statistically significant differences in resistance and reactance do not occur after the first set of repetitions at any frequency for both groups of participants. The earliest occurrence of statistically significant differences ($p < 0.05$)

Table 1
Median resistances (Ω) collected at 10 kHz, 50 kHz, and 100 kHz pre-fatigue and after each set of repetitions.

Freq.	60% Group Resistance (Ω)										
(kHz)	Pre	1	2	3	4	5	6	7	8	9	10
10	42.17	43.03	41.98	42.35	40.86*	40.38*	39.82*	39.35*	39.19*	38.86*	38.58*
50	31.48	31.04	30.77	30.68*	30.57*	30.60*	30.12*	29.93*	30.04*	29.79*	29.81*
100	25.96	25.32	25.32	25.04*	25.06*	25.07*	24.74*	24.51*	24.73*	24.49*	24.60*
75% Group Resistance (Ω)											
10	42.78	42.67	42.48	42.00	41.45	40.12*	39.81*	39.69*	40.15*	39.82*	39.74*
50	35.19	34.31	33.77	33.48	33.39*	32.86*	32.75*	32.94*	32.72*	32.41*	32.54*
100	31.43	30.09	29.79	29.77	29.53*	29.07*	29.08*	29.25*	29.02*	28.83*	28.88*

Note: (*) denotes statistical significance ($p < 0.05$) using Bonferroni correction compared to pre-fatigue value.

Table 2
Median reactances (Ω) collected at 10 kHz, 50 kHz, and 100 kHz pre-fatigue and after each set of repetitions.

Freq.	60% Group -Reactance (Ω)										
(kHz)	Pre	1	2	3	4	5	6	7	8	9	10
10	7.16	7.37	6.92	6.80	6.37	6.22*	5.82*	5.76*	5.66*	5.58*	5.50*
50	10.52	10.56	10.14	10.02	9.71*	9.44*	9.32*	9.09*	8.97*	8.76*	8.66*
100	9.29	9.36	9.29	9.17	8.86*	8.81*	8.65*	8.55*	8.49*	8.45*	8.17*
75% Group -Reactance (Ω)											
10	6.11	6.65	6.49	6.22	5.82	5.38	5.36	5.21*	5.14*	5.14*	4.98*
50	8.37	8.48	8.68	8.58	8.34	8.16	8.00	7.88*	7.90*	7.78*	7.72*
100	7.67	7.54	7.54	7.50	7.51	7.54	7.34*	7.09*	7.10*	7.16*	6.86*

Note: (*) denotes statistical significance ($p < 0.05$) using Bonferroni correction compared to pre-fatigue value.

Table 3
Median phase angle (°) collected at 10 kHz, 50 kHz, and 100 kHz pre-fatigue and after each set of repetitions.

Freq.	60% Group Phase Angle (°)										
(kHz)	Pre	1	2	3	4	5	6	7	8	9	10
10	−8.16	−8.53	−8.39	−7.81	−7.82	−7.60	−7.58*	−7.38*	−7.51*	−7.61*	−7.41*
50	−17.89	−18.38	−18.60	−18.04	−18.14	−17.74	−17.56	−17.18*	−17.23*	−17.25*	−16.85*
100	−19.75	−20.23	−20.45	−19.95	−20.00	−19.52	−19.31	−19.14	−19.14*	−18.98*	−18.55*
75% Group Phase Angle (°)											
10	−7.82	−8.82	−8.78	−8.26	−7.92	−7.61	−7.35	−7.15*	−7.08*	−6.93*	−6.84*
50	−13.72	−14.20*	−14.20	−14.16	−13.73	−13.39	−13.47	−13.40	−13.38	−13.20	−13.01*
100	−13.54	−13.66	−13.69	−13.83	−13.43	−13.16	−13.46	−13.24	−13.16	−13.00	−12.87

Note: (*) denotes statistical significance ($p < 0.05$) using Bonferroni correction compared to pre-fatigue value.

at all frequencies is observed at sets 4 and 5 for the 60% and 75% 1-RM group resistances, respectively, and at sets 5 and 7 for the reactances of the 60% and 75% 1-RM groups.

The decrease in resistance observed in the participants of this study is expected to result from the muscle swelling that occurs as a result of the exercise. While muscle swelling was not measured in this study, Yasuda et al. [29] reported increases of the bicep brachii muscle thickness assessed using ultrasound imaging after multiple sets of curl exercises [29]. The muscle swelling reported by Yasuda et al. [29] showed increases with every additional set of repetitions, which supports the trend of decreasing resistance with additional sets of repetitions in this study. Muscle swelling is expected to increase the localized fluid volume and available charge carriers in the region, reducing the overall tissue resistance. Additional support for the decrease in resistance being attributed to swelling and increases of localized fluid in the biceps tissue is provided by a study from Li et al. [30] who assessed the impedance changes in the biceps brachii after botulinum toxin injections [30]. Li et al. [30] reported averaged multi-frequency decreases in the bicep resistances ranging from 0.35 Ω to 5.57 Ω in study participants, which is within the same ranges observed in this study. This directly supports that increases in localized tissue fluids decreases the measured tissue resistance. A limitation of this work was not directly measuring the swelling, which should be further investigated to quantify the association between measured resistance and swelling.

Recent studies by Nescolarde et al. reported decreased 50 kHz reactances during comparisons of non-injured and injured limbs in professional athletes 24 h after injury, with greater decreases observed for higher grades of injury [9]. Those study results support that the reactance component does change as a result of disruption to the muscle structure through injury. The mean reactance showed a 17.5% reactance difference between the injured and non-injured limbs in the athletes with a grade I injury (minor strain without loss of function or strength, diffuse edema and structural abnormalities with less than 5% of the whole muscle involved) [9]. These differences were larger than those observed in this study, with 50 kHz mean reactance differences ranging from 8.0% to 10.6% in the data from the left and right biceps of both intensity groups. The reactance component may serve as a marker of the muscle state of health which warrants further investigation of changes that result from fatigue and injury. Interestingly, Li et al. did not report statistically significant differences in the reactance component of the bicep tissue measurements after botulinum toxin injections which may indicate that changes in localized fluid alone do not change the reactance and that changes in the tissue structures potentially from damage may be their cause. However, this requires further measurement of both tissue impedance and markers of tissue damage to validate.

In both reactance and resistance datasets, statistically significant differences are observed at earlier sets for the higher

frequency measurements than the lower frequency measures. That is, the resistance measures in Table 1 show statistically significant differences for the 50 kHz and 100 kHz values at set 3 and 4, for the 60% and 75% 1-RM groups, respectively. One set earlier for both groups than the statistically significant values are observed for the 10 kHz values. Similarly, the statistically significant 50 kHz and 100 kHz reactance in Table 2 for the 60% 1-RM group appear 1 set before the 10 kHz values; and the 100 kHz reactance for the 75% group shows the same trend. While this may be interpreted as the physiological changes that result from fatigue causing changes that impact the high-frequency tissue behaviour sooner in-time, it may also be an artifact of the method for data collection in this study. The measurements were collected using a stepped-sine approach which requires the application of a single-frequency to the tissue under measurement to characterize the behaviour at this specific frequency. This requires a finite amount of time before the frequency is stepped to a new value and the process repeated. In this work, measurements were collected starting at 10 kHz and required approximately 0.2 s per frequency to measure, with 68 frequencies measured between 10 kHz and 100 kHz. This required approximately 13.6 s to measure this range of frequencies. During this time, the electrical properties of the bicep tissues may still be changing due to the effects of the exercise protocol. If true, then the 10 kHz impedance may have had a larger decrease if measured at the same instants in time as the 50 kHz and 100 kHz measurements. To identify if the earlier changes at higher frequency are a true feature of the tissue or an artifact of the test method, future studies of time-variant bio-impedance systems using stepped-sine excitations should integrate the methodologies introduced by Louarroudi and Sanchez [31].

EIM phase angle has been widely investigated as the impedance feature of interest in neuromuscular studies. The 50 kHz phase angle was used to track ALS progression [32] and has been shown to gradually increase in healthy children while children with untreated spinal muscular atrophy showed stable values [33]. In regards to muscle injury, significant reductions in 50 kHz phase angle were reported in mice after eccentric contractions were applied to induce injury in quadricep muscles [27]. In this study, statistically significant changes in 50 kHz phase angles were observed in both groups. With those changes observed at sets 7 and 10 for the 60% and 75% groups respectively. Additionally, statistically significant differences in 10 kHz phase angle was also observed in both groups in this study. However, while the 60% group did have statistically significant differences for the 100 kHz phase angles, no statistically significant differences were observed in the 75% group (though there were statistically significant differences in comparisons between the different timepoint measurements in this group). Another notable fact is that the phase angle may not change with the exercise sets monotonically even when a general decreasing trend can be observed for corresponding resistance and reactance. This causes a statistically significant change of phase angle at the first set measured at 50 kHz of 75% group, shown in Table 3. The non-monotonic change of phase angle could be due to the different rates of change for the corresponding resistance and reactance. This may support that monitoring resistance and reactance independently may provide more insights regarding the relation between exercise and measured bioimpedance. This requires further investigation though to identify which EIM feature (resistance, reactance, phase angle) is most appropriate for tracking tissue changes and to link them to the specific physiological mechanisms that are occurring as a result of exercise-induced fatigue.

5. Conclusion

This study collected the multi-frequency electrical impedance of the biceps tissue in 17 participants throughout a 10 set exercise-protocol to induce fatigue, with participants grouped in two different intensities related to participants one-repetition maximum strength. The changes in resistance, reactance, and phase angle showed statistically significant magnitude decreases compared to the pre-fatigue measures, with the significant resistance changes occurring at earlier timepoints in the protocol than the reactance changes. These results support that the electrical impedance of tissues may be an effective monitor to quantify the changes that occur in localized tissues, including muscle swelling and damage, throughout a fatiguing activity and warrant further investigation.

Conflicts of interest

None declared.

Funding

None declared.

Ethical approval

The study was approved by the Institutional Review Board of The University of Alabama (16-OR-234).

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