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Original Research

Investigating the Sensitivity of Phase Angle to Eccentric Exercise of the Biceps Brachii: A Brief Report

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Abstract

International Journal of Exercise Science 19(4): 4005, 2026. Phase Angle (PhA), a measure of cellular health that is collected during bioelectrical impedance analysis (BIA), is sensitive to fluid shifts, which occur during high-intensity exercise, but its role in tracking these changes during muscular recovery is unclear. Therefore, the purpose of this study was twofold; the first objective was to investigate the sensitivity of PhA to muscular damage following an acute bout of eccentric exercise. The second objective was to investigate the potential use of PhA in tracking muscular recovery in the 72 hours following exercise. In this study, participants performed a maximal voluntary isometric contraction (MVIC) in both nondominant (EX) and dominant (CON) arms, then completed sets of 10 eccentric biceps curls at 45°•s^{-1} using the EX arm. After each set, participants rested for one minute, then completed an MVIC in the EX arm to assess strength loss. This cycle continued until MVIC decreased by ≥60%. Pre- and post-exercise BIA scans measured segmental PhA and compartmental fluid in both arms. Subjective soreness and pressure-pain threshold (PPT) in the EX arm were recorded. Participants returned for three consecutive days for assessments of MVIC and BIA in both arms, and soreness and PPT in the EX arm. A 2x5 RMANOVA tested differences between EX and CON arms for impedance variables and MVIC. A 1x5 RMANOVA tested differences in PPT and visual analog scores (VAS). Significant differences were found in EX arm MVIC ($p<0.001$, $\eta p^2= 0.109$), extracellular water ($p<0.001$, $\eta p^2= 0.003$), intracellular water ($p=0.001$, $\eta^2_p= 0.005$), and total body water ($p=0.004$, $\eta p^2= 0.001$). No significant differences were observed in EX arm PhA ($p=0.784$), PPT ($p=0.079$), or soreness ($p=0.583$). While exercise produced notable strength impairments (average percent change pre-to-post protocol: -35.24%) and fluid shifts, PhA and pain measures were unaffected. Thus, based on the results of the current study, PhA may not be sensitive to or related to classic indices of muscle damage.

Keywords: Muscle recovery, pain-pressure threshold, strength loss, eccentric exercise, compartmental body water, phase angle

Introduction

Exercise-induced muscle damage (EIMD) can occur from any activity that an individual is not accustomed to, but particularly eccentric contractions.[1] EIMD severity depends on several factors, including movement velocity, the volume of eccentric load, the magnitude of force produced, the duration of the exercise bout, and exercise intensity.[1] The degree of EIDM dictates the degree of inflammatory response activation, and the greatest inflammatory response is typically seen after extreme exercise bouts, such as ultra endurance events or marathons, or eccentric

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actions.[1,2] These responses lead to delayed onset muscle soreness (DOMS) and a series of changes in the muscle tissue itself, including changes to the sarcolemma permeability, damage to the cell membrane, and structural changes of both the sarcomere and the cytoskeleton.[3] These changes in the muscle tissue from EIMD results in functional decrements, such as disruption of muscular strength and force production capabilities of the tissue.[3] Strength and force production losses of 20% or more have been seen following EIMD, and the degree to which performance is decreased usually determines the recovery time needed to return to normal function.[4] Mild decreases in performance typically take 12 to 48 hours to resolve, whereas severe performance decreases and related symptoms can take as much as three weeks to resolve.[1]

Following EIMD, DOMS sets in rapidly, accompanied by symptoms such as soreness, swelling, decreased range of motion, and decreased force-generating capacity of the affected muscles.[5,6] These symptoms typically last from 2 to 9 days and dissipate over time, with severity and duration of the symptoms being heavily dependent on the intensity of the exercise, the degree of eccentric actions, and the training status of the participant.[1,3,7] The muscular recovery process also depends on these factors; responsiveness to eccentric exercise,[8] the amount of damage done,[7,9] and past exposure to eccentric exercise[10] are all major determinants of how long total muscular recovery will take. Other factors, such as sleep, nutrition, and hydration, can also play a large role in improving the efficiency of muscular recovery.[6,9,11] Direct measures of muscle damage, such as assessing the actual tissue and looking for Z-line streaming are difficult and require muscle biopsies.[4,5] Thus, indirect methods of measurement are more common, such as looking at the degree of strength loss via MVIC assessment, joint range of motion, inflammatory markers, and soreness.[5,12] Assessing muscular soreness is most often done using pressure algometry (i.e., the pain-pressure test), visual analog scales[13,14] and ratings of perceived exertion (RPE).[15]

As the muscle undergoes the recovery process, soreness and swelling are reduced, range of motion returns to pre-exercise values, and force production is restored, as measured by strength returning to or above pre-EIMD levels.[5,6,16] This process involves an inflammatory response, the activation of satellite cells, and the return of functional capacity (i.e., strength).[6] The inflammatory response following EIMD involves shifts in body water to different compartments in the muscles used during exercise, altering the amount of water in each compartment.[6] Body water is stored intracellularly (ICW), extracellularly (ECW), and can be measured throughout the entire body using total body water (TBW).[6] It has been shown that body water changes following chronic resistance training are common, with Ribeiro et al., (2014) finding that a 16-week resistance training program was sufficient to significantly increase TBW and ICW in both men and women. Although not as widely studied, it has also been shown that acute, localized bouts of upper body resistance training can cause acute increases in TBW, ICW, and ECW in the active tissue.[17]

Phase angle (PhA) is defined as the shift that exists between total voltage and total electrical current. PhA reflects the ratio between reactance and resistance within functional cells in the human body. Reactance is a measure of a cell's volume and is an indirect measure of the cell mass. At the same time, resistance is offered by body fat and extracellular water and can be used as an indirect measure of cell membrane integrity.[18] PhA is a variable commonly measured during bioelectrical impedance analyses (BIA) and has gained popularity as a tool that can be used to assess the overall and cellular health of an individual, by estimating the cell integrity and mass of functional cells within the body.[19] PhA is dynamic throughout life, varies from person to person, and is impacted by many different factors.[19] Factors that influence PhA include gender, age, physical activity, BMI, and body composition.[20] Due to the ease of flow of electricity through

water, fluid within the body can also influence PhA values.[19]

Changes in body water due to exercise induced damage could potentially impact both whole-body and segmental PhA values, as PhA is sensitive to inflammation and body water changes. Exercise-induced changes in reactive oxygen species concentration could further influence PhA values. The relationship between inflammation in damaged muscle tissue and performance should also be considered; mild inflammation is associated with mild performance decrements,[6] and therefore, it may be reasonable to hypothesize that PhA could remain altered until the recovery process is complete and normal function and inflammatory activity are restored. PhA is commonly used as a tool in clinical settings to assess the prognosis of chronic illnesses and the overall health of patients, however it has not yet been studied as a potential tool for monitoring EIMD or the recovery process after eccentric protocols. Long-lasting increases in PhA are common with participation in resistance training longer than 8 weeks,[21] but acute changes in PhA have not been investigated. PhA could potentially be used as a tool to monitor fluid shifts in muscle tissue and could provide insight into the muscular recovery process with regular measurements; however, the sensitivity of PhA to an acute bout of eccentric exercise is unknown.

Therefore, the primary purpose of this study was to investigate the sensitivity of PhA to acute bouts of maximal eccentric exercise of the biceps brachii in healthy, fit individuals. It was hypothesized that segmental PhA of the arm used in the exercise protocol would be impacted and altered by the acute bout of eccentric exercise; it was also hypothesized that there would be significant differences in ICW, ECW, and TBW in the arm used in the exercise protocol. A secondary purpose was to investigate and compare the relationships between PhA and the currently established indirect markers of muscle damage, including soreness and MVIC values; these markers were included to demonstrate decreases in force production and changes in transient pain and to confirm that the exercise protocol used in the study induced muscle damage sufficient to induce inflammation and other symptoms associated with EIMD. Finally, the study aimed to explore whether the changes in PhA were associated with these established indirect markers of muscle damage. It was hypothesized that PhA would have a positive association with currently established indirect markers of muscle damage; it was also hypothesized that VAS and PPT would change significantly due to eccentric exercise.

Methods

This research was approved by Ohio University's IRB (IRB-FY24-154) and was fully compliant with ethical standards and informed consent procedures. A pre-screen eligibility survey was sent to the Ohio University student body via email. Questions included those regarding physical activity participation, chronic illness diagnoses, injuries, and the presence of internal medical devices. Following the assessment of eligibility from the pre-screen survey, participants were invited to participate in the study. They were sent the consent to review before their first lab visit, at which they were given the opportunity to ask any questions. Written informed consent was provided before commencing participation (Table 1).

Participants

Table 1. Anthropometrics of Participants.

Gender	N	Age (years)	Weight (kg)	Height (cm)	BMI
F	4	20 ± 1	65 ± 12	149 ± 20	32 ± 14
M	8	21 ± 3	81 ± 8	179 ± 6	25 ± 2

Table 1 summarizes the anthropometric measurements of the participants. There were 12 participants in total, 8 male and 4 female. Sex was self-reported by participants. To be eligible for participation, it was required that participants be physically active and participate in moderate or vigorous activity at least three days per week. It was not required that participants be actively engaged in upper-body resistance training specifically. Participants were excluded if they were under the age of eighteen or over the age of 28. Participants were also excluded if they had any known chronic illness, such as heart disease, high blood pressure, or kidney disease, or if they had any history of rhabdomyolysis, complex regional pain syndrome, or reflex sympathetic dystrophy. Individuals with any electronic medical implants were also excluded. Individuals with biceps, shoulder, or elbow injuries in the past year were also excluded.

A power analysis was conducted using data from Hubal[8] to establish the number of total participants needed for most participants to be classified as responsive to eccentric exercise. Responsiveness to eccentric exercise is established based on the immediate decrease in MVIC values seen post exercise.[8] Individuals who experience strength decreases of 30% or higher are considered high-responders, individuals who experience strength loss between one and 29% are considered low-responders, and individuals who experience no strength loss or an increase in strength immediately post-exercise are classified as non-responders.[8] A priori power analysis was conducted using G*Power for paired-samples *t*-tests (two-tailed; $\alpha = .05$, $1 - \beta = .80$). For responders, assuming a large effect size ($dz = 0.91$), the required sample size was $n = 12$. For non-responders, assuming a moderate effect size ($dz = 0.51$), the required sample size was $n = 32$. Given this variability and potential attrition, a target sample size of 24 was established. The study was not designed or powered to assess sex-specific differences; therefore, sex was included for descriptive purposes only. This research was carried out fully in accordance with the ethical standards of the International Journal of Exercise Science.[22]

Protocol

Participants were introduced to the methodology during the initial lab visit, after reviewing and signing the informed consent form. The exercise protocol of this study was completed using a HUMAC NORM isokinetic dynamometer (CSMI, HUMAC NORM™, Stoughton, MA). In order to make the exercise feel as natural as possible and to simulate bicep curls in a gym or fitness setting, the standard HUMAC NORM wrist/shoulder adapter with the standard handle was used as the attachment to the dynamometer, and participants were positioned in a seated upright position. To configure the proper setup, participants were asked to sit in the HUMAC NORM and request the research team to make any necessary changes to the chair height, the height of the dynamometer, or the height of the handle that would be used for the biceps curls to be able to move through their range of motion smoothly and naturally. When configured, participants were then asked to complete an MVIC measurement practice to familiarize themselves with the motion. Afterwards, participants were exposed to one set of 10 eccentric biceps curls at $45° \cdot s^{-1}$ followed by one minute of rest. This portion of the familiarization was also submaximal and was implemented to allow participants to become accustomed to their set range of motion and the speed of movement. Measurements taken during the familiarization session were not used in statistical analysis.

Following familiarization, initial MVIC measurements were taken in both the EX and CON arms, with arm order randomized at each visit. MVIC values were recorded at familiarization, pre-eccentric exercise (ECC), post-ECC, and 24-, 48-, and 72-hours post-ECC. Measurements were taken at 90° elbow flexion[23] with approximately one minute rest between arms to adjust the

isokinetic dynamometer. The HUMAC NORM was then configured for the EX arm. Range of motion was set by having participants fully flex the EX arm, which the researcher extended by 15°, and fully extend the arm, which was then flexed by 15°, to prevent injury and ensure proper rep completion. Participants performed sets of 10 maximal eccentric biceps actions at 45°•s□¹ using the EX arm. After one minute of rest, MVIC of the EX arm was remeasured at 90° for 5 seconds, with peak torque recorded for baseline comparison. Participants then rested for 30 seconds before the next set of biceps curls. If MVIC values dropped ≥60% from baseline, participants rested for two minutes before retesting. If the decrease was sustained, task failure was confirmed, and the protocol was ended. If not, participants continued with additional sets and MVIC tests until either task failure occurred or the maximum number of sets (10) were completed.

Impedance variables (PhA, ICW, ECW, and TBW) were collected at each lab visit using bioelectrical impedance analysis (BIA; InBody770, InBody USA, Cerrito, CA) in triplicate at familiarization, before the ECC, immediately post ECC, and 24-, 48-, and 72- hour post ECC (before and after the MVIC measurements). PhA values for both EX and CON arms were collected for each analysis, and these segmental PhA values were reported. The averages of PhA, TBW, ECW, and ICW from the triplicate measurements were used in data analysis. Participants were asked to avoid eating and drinking directly before the BIA tests and asked to adhere to their normal exercise habits (with the exclusion of strenuous exercise throughout the monitoring period) to avoid unanticipated fluctuations in BIA measurements. Reliability and validity of the InBody 770 regarding assessing body composition, compartmental body water, and impedance variables including PhA has been established previously in current literature.[24]

Soreness was measured using both objective and subjective measures. For objective measures of soreness, a Wagner pressure algometer (Force One™ FDX, Wagner Instruments, Greenwich, CT) was used to perform a pain threshold test (PPT). The pressure algometer was applied to the belly of the biceps brachii (approximately 70% the distance between the acromion and the lateral epicondyle of the humerus) of the EX arm, and pressure was slowly increased until participants indicated pain; the PPT value was recorded in Newtons. Use of a pressure algometer in this manner to measure applied force has been shown to be both a valid and reliable measure.[25] Participants were then asked to rate their pain using a 100mm visual analogue scale (VAS). The use of a 100mm VAS has previously been shown to be both a valid and reliable measure for assessing acute pain.[26] This process was repeated three times with a 30-second rest interval between trials. The tests were repeated at the 24-, 48, and 72-hour check-ins following the exercise protocol. Soreness measurements were only performed in the EX arm.

Statistical Analysis

Raw data was exported to a Microsoft Excel file for sorting and organization. Data was then exported to Jamovi version 2.3.28 (The Jamovi Project, 2025), where all the statistical procedures were conducted. Data from all participants who completed the study was used for analysis, regardless of responsiveness to eccentric exercise as classified by pre- and post-exercise MVIC values. A 2x5 repeated measures Analysis of Variance (ANOVAs) was used to test differences between the EX and CON arms for each impedance variable (PhA, ECW, ICW, and TBW) and MVIC values at all time points. A 1x5 repeated measures ANOVA was used to test differences for both PPT values and VAS scores across time. Where significant differences were found, Tukey's post hoc analysis was conducted. Pearson's correlations were calculated to evaluate the potential relationships between MVIC, PhA, pain-pressure threshold, and VAS. Effect sizes for ANOVA results were reported as partial eta squared (ηp^2) and interpreted as small (ηp^2 =

0.01–0.05), medium (ηp^2 = 0.06–0.13), and large ($\eta p^2 \geq 0.14$).Pearson's correlation coefficients (*r*) were calculated to evaluate relationships between MVIC, PhA, PPT, and VAS, Effect sizes were interpreted as small (r = 0.10–0.29), moderate (r = 0.30–0.49), and large (r ≥ 0.50). An alpha level of .05 was used for all statistical tests.

Results

Participants had varying levels of responsiveness to the ECC used in this study. Most participants were classified as high responders, having a decrease in MVIC values of 36% or more (n=8). Other participants were classified as low responders with MVIC decreases of 35% or less (n=3), while one participant was classified as a non-responder due to an increase in MVIC values (Figure 1).

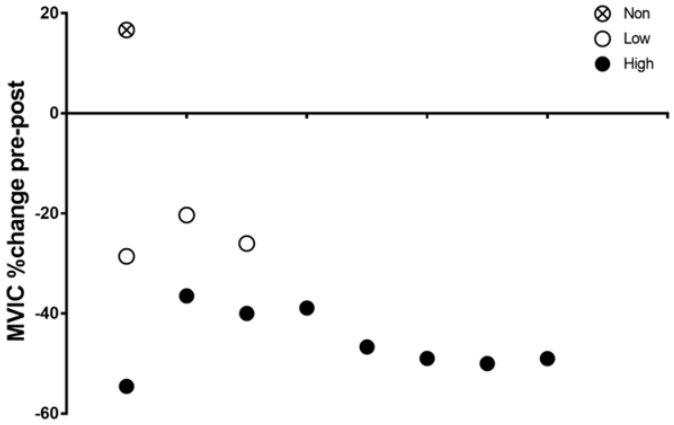

Figure 1. Responsiveness of Participants to Eccentric Exercise.

Muscular Strength Measurements

Figure 2 summarizes the changes in MVIC values in participants at all lab visits. MVIC was significantly lower immediately post-ECC compared to pre-ECC (F(4) = 11.8, ηp^2= 0.109, p<0.001, average percent change=-35.24) in the EX arm only, indicating a meaningful proportion of variance explained. MVIC recovered and was greater at 24-hours, 48-hours, and 72-hours compared to post-ECC (F(4)= 11.8, ηp^2= 0.517, p<0.001 for all), demonstrating a very large effect size.

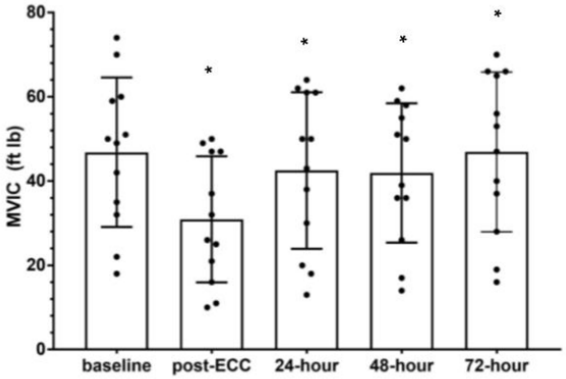

Figure 2. Mean and Standard Deviation of MVIC Values.

Note: *Denotes statistical significance in the EX arm between pre-MVIC and post-ECC (F(4)= 11.8, ηp^2= 0.109, p<0.001), and between post-ECC, 24hr, 48hr, and 72hr (F=(4)= 11.8, ηp^2= 0.517, p<0.001 for all).

Torque Measurements

Peak torque values for each participant were evaluated by set to examine changes over time. Figure 3 displays changes in torque values for each participant compared to the mean torque changes for all participants over the course of the ECC. The average number of sets completed by participants was 8, with most participants completing 7 to 10 sets, and one participant completing only 3 sets before reaching task failure.

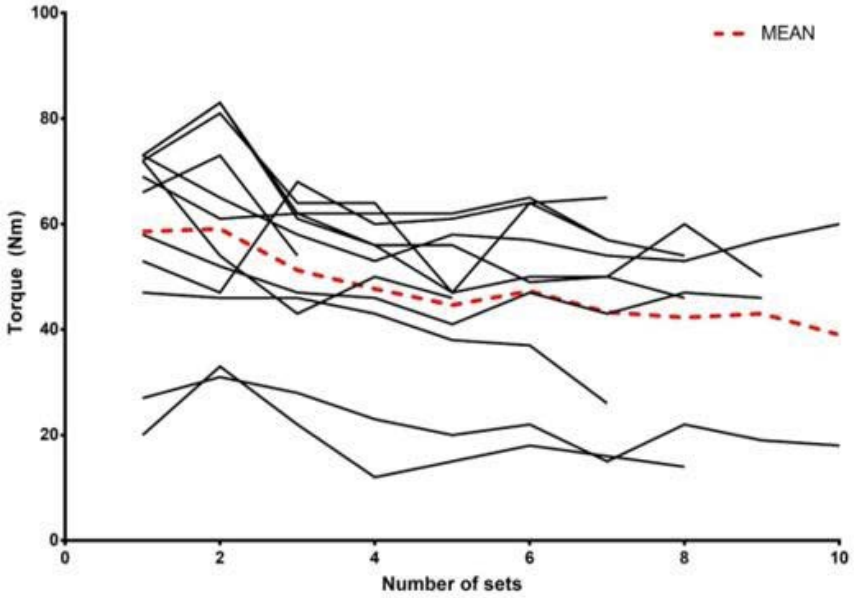

Figure 3. Torque Values of Participants Over Time.

Pain Tolerance and Visual Analog Scores

Table 2 shows the differences in pain tolerance scores and visual analog scores measuring soreness of the participants throughout the study. There were no main effects for time in either pain tolerance ($F1, 4, p = 0.079, \eta p^2 = 0.031$) or visual analog scores ($F1,4, p = 0.583, \eta p^2 = 0.020$); however, pain tolerance was lowest and visual analog scores were highest at the 24 hour and 48-hour visits, indicating that those time periods were when participants were experiencing the most severe symptoms of DOMS.

Table 2. Muscular Soreness Measurements.

Time	Pain Tolerance (Newtons)	Visual Analog scores (0-100 mm)
Baseline	16.21 ± 10.07	20.50 ± 11.63
Post-ECC	16.04 ±10.50	23.14 ± 8.37
24 hours	12.54 ± 6.63	24.79 ± 16.35
48 hours	13.44 ± 6.84	25.93 ± 18.21
72 hours	15.48 ± 8.58	27.04 ± 21.19

Bioelectrical Impedance Analysis

Figure 4 summarizes the changes found in PhA. There were no statistically significant interaction effects ($F1, 8= 0.02, p=0.999, \eta p^2=0.000$) and no statistically significant main effects found for PhA ($F1, 4= 0.23, p= 0.912, \eta p^2=0.003$). For TBW (Figure 5), there was a significant interaction effect between arms ($F1,8=10.90, p<0.001, \eta p^2=0.001$) and a significant main effect for time ($F1,$

4=16.40, p<0.001, ηp^2=0.001). Specifically, the EX arm was significantly greater vs. the control arm at baseline (p<0.001), post-ECC (p<0.001), 24-hours (p<0.001), 48-hours (p=0.040), and 72-hours post (p=0.040). Additionally, post-ECC was significantly greater vs. all other time points (p<0.001 for all). For ECW (Figure 6), there was a significant interaction effect between arms (F1,8=7.19, p<0.001, ηp^2=0.001) and a significant main effect for time (F1, 4=18.54, p<0.001, ηp^2=0.003). Specifically, the EX arm was significantly greater vs. the control arm at baseline (p=0.044), post-ECC (p=0.030), 24-hours (p=0.042), 48-hours (p=0.039), and 72-hours post (p=0.038). Additionally, post-ECC was significantly greater vs. all other time points (p<0.001 for all). For ICW (Figure 7), there was no interaction effect (F1, 8=1.46,p=0.220, ηp^2=0.000); however, there was a significant main effect for time (F1, 4=22.80, p<0.001, ηp^2=0.005). ICW was significantly greater post-ECC compared to all other points (p<0.001 for all).

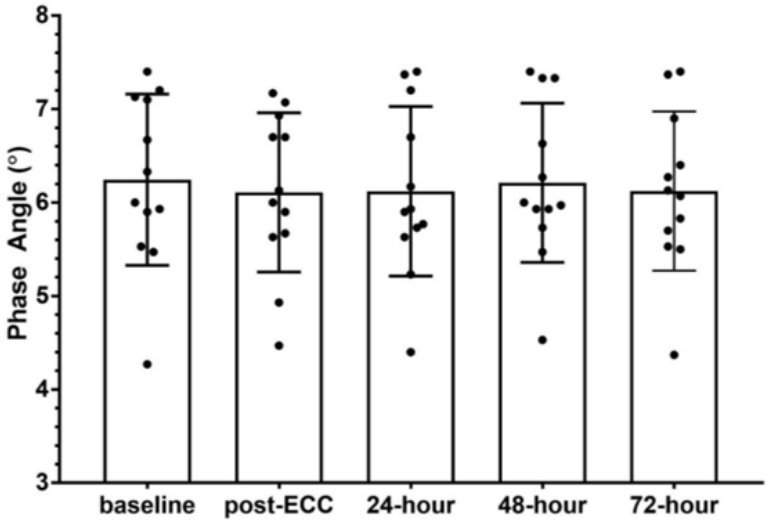

Figure 4. PhA Analysis.

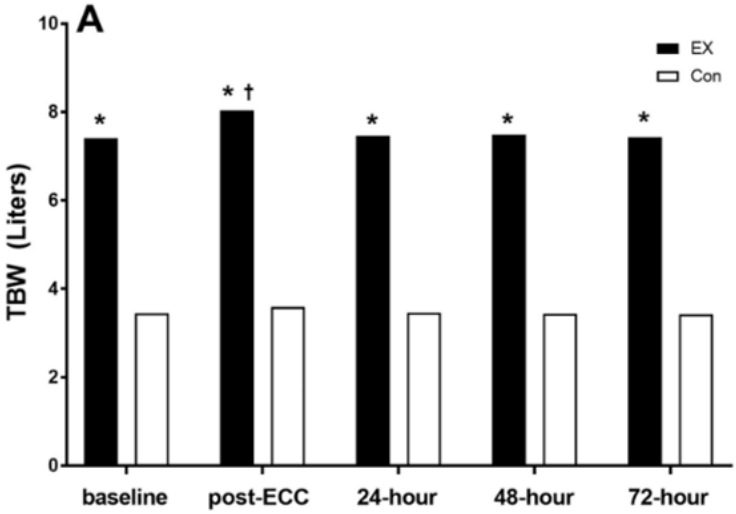

Figure 5. Changes in Total Body Water Measurements Over Time and Between EX Arm and Control Arm.

Note. *Denotes significantly greater post-ECC vs. all other time points (p<0.001). †Denotes significantly greater in EX arm vs. CON arm at baseline (p<0.001), post-ECC (p<0.001), 24-hours (p<0.001), 48-hours (p=0.040), and 72-hours post (p=0.040).

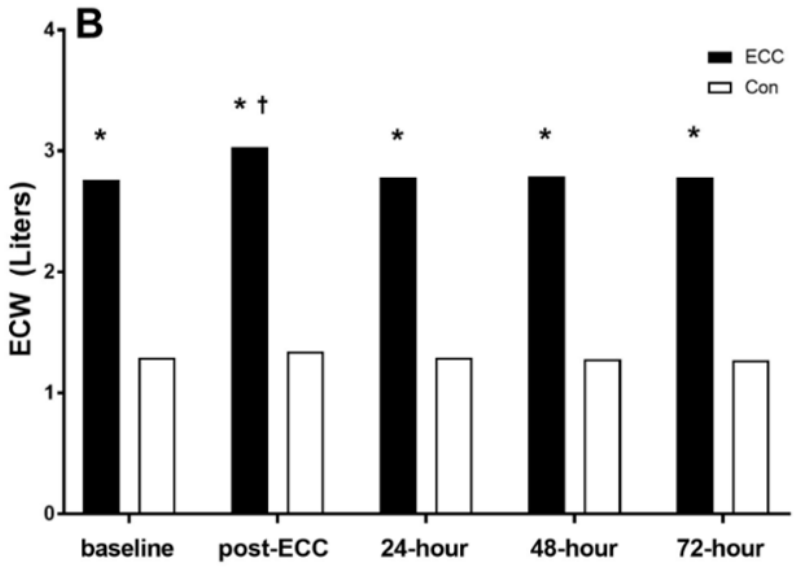

Figure 6. Changes in Extracellular Water Measurements Over Time and Between EX Arm and Control Arm.
Note. *Denotes significantly greater post-ECC vs. all other time points (p<0.001). †Denotes significantly greater in EX arm vs. CON arm at baseline (p=0.044), post-ECC (p=0.030), 24-hours (p =0.042), 48-hours (p=0.039) and 72-hours post (p=0.038).

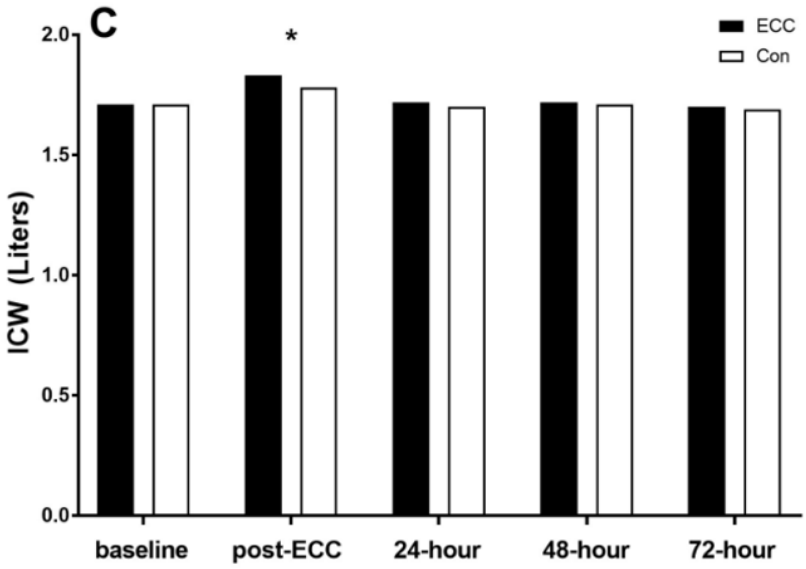

Figure 7. Changes in Intracellular Water Measurements Over Time and Between EX Arm and Control Arm.
Note. *Denotes significantly greater post-ECC vs. all other time points (p<0.001).

Relationships Between Variables

There was a moderate positive relationship between PPT scores and MVIC values (r=0.509, p<0.001). There was a moderate negative relationship between MVIC values and VAS (r=-0.451, p<0.001). There was no statistically significant relationship found between MVIC and PhA (r=0.193, p=0.139), between PhA and PPT (r=0.075, p=0.570), or between PhA and VAS (r=0.199, p=0.128).

Discussion

This study examined the sensitivity of PhA to acute bouts of maximal eccentric exercise of the biceps brachii in healthy, fit individuals and to determine the effect of this type of exercise on the currently established indirect markers of muscle damage, including soreness and MVIC values, as well as impedance variables. This study also investigated and compared the relationships between PhA and the currently established indirect markers of muscle damage to determine if PhA is sensitive enough to EIMD and muscular recovery.

This study aimed to used indirect markers of EIMD, such as strength loss, to ensure than an adequate amount of muscle damage was incurred for investigational purposes; when muscular damage is present, muscular strength is compromised due to membrane damage, structural changes, and trauma-induced disruption to force production, causing a decreased ability of the sarcomere to complete excitation-contraction coupling.[3] To indirectly investigate muscle damage in the current study, MVIC values were recorded for each participant in both arms following sets of 10 eccentric biceps curls until task failure. MVIC has been used extensively in the existing literature as a functional outcome of strength loss and served as the metric of establishing sufficient strength loss in participants for the purpose of this study.[3,4,5] Despite a significant loss in muscular strength production, evidenced by sustained decreases in MVIC, and significant body water fluid shifts, there was no significant difference in PhA, muscular soreness or pain tolerance scores throughout the 3-day recovery period.

The average number of eccentric curl sets completed was 8.25, with one participant completing only 3 sets and several participants completing all 10. Responsiveness varied considerably, as expected, since pre-existing literature has shown that individuals are classified as high-, low-, and non-responders to eccentric exercise, with strength losses ranging from 50% to 20%.[8] This variability was evident here: MVIC changes ranged from -55% to -20%, with one participant showing a 17% increase. Most decreases (−36% to −54%) classified participants as high responders to eccentric exercise.[8]

Peake et al,[6] found that when muscle strength decreases by <20% immediately post-exercise, it will typically be recovered within 2 days, whereas with decreases of about 50% immediately post-exercise, strength is typically compromised as far as 7 days after the exercise bout. Due to the extent of strength loss in participants, it was anticipated that participants would have significantly impacted muscular strength throughout the study. While some participants never returned to their baseline MVIC values, most participants recovered from the exercise at the 48 or 72-hour mark. Foundational research on muscle damage and recovery following eccentric exercise has reported that typical responses to maximal eccentric actions is typically an immediate 50-60% decrease in strength, and a linear recovery time of 2 weeks post-exercise.[27] Other literature suggests recovery time may be much longer, with the halftime of the recovery of submaximal eccentric actions of the elbow flexors possibly being as long as 5 to 6 weeks.[16] However, newer research demonstrates that the recovery time associated with eccentric exercise depends on immediate strength decreases following the initial bout; individuals with decrements of ≤20% are usually fully recovered within 2 days[7,9] whereas individuals with immediate decrements in strength of around 50% will typically experience decreased strength as far out as 7 days after the exercise.[28,29] In the current study, most participants showed a significant decline in force production, with MVIC decreasing 35% from pre- to post-protocol. Recovery was incomplete at 24 hours (10% decrease) and 48 hours (9% decrease), with full recovery by 72 hours. It is important to note that the repeated bout effect associated with eccentric exercise may play an important role in recovery

time as well. Paulsen et al (2009), found that participants recovered faster after a second bout of eccentric exercise than a first bout only 3 weeks prior, with no additional training; therefore, the amount of eccentric exercise an individual does regularly may have a large impact on their recovery time and somewhat preserve their force-generating ability after an eccentric exercise bout.

EIMD also induces an inflammatory response in the muscle, causing fluid shifts, edema, and muscular soreness. When muscle tissue undergoes physiological injury, such as what is sustained during unaccustomed or eccentric exercise, the damaged or stressed tissues release inflammatory signals to induce a localized, acute inflammatory response.[30] This acute inflammatory response causes increased microvascular permeability and subsequent plasma leakage into surrounding tissues.[31] This leakage, known as edema, causes temporary pressure against nociceptors, resulting in pain with movement and with additional external pressure, in addition to the secretion of molecular mediators that can produce pain sensitization of the area.[14,32] Following confirmation of muscle damage, impedance derived fluid-variables (ICW, ECW, and TBW) were examined to provide mechanistic insight into the physiological response to EIMD. It was found that from baseline to post-ECC, ICW, ECW, and TBW were all significantly higher in the EX arm compared to the CON arm. TBW and ECW remained significantly different from baseline to 24, 48, and 72 hours post ECC when comparing the EX arm to the CON arm, and ICW had returned to near baseline levels at 24 hours post-ECC. This was expected, as the degree of the inflammatory response is related to the intensity of the exercise and the number of eccentric actions, and then influences fluid shifts throughout body compartments.[1] Fluid tends to shift inside the muscle fibers during exercise, particularly during resistance training, and while long-term resistance training programs (≥8 weeks) cause the most dramatic fluid shifts,[21] acute bouts can also alter body water. Localized, acute resistance training, particularly in the upper body, has been shown to increase TBW, ICW, and ECW in the active segment,[17] and eccentric exercise in one arm can decrease impedance values in biceps tissue.[33] Differences in body water compartments between opposing segments of the same individual are also common, influenced by factors such as muscle mass, hydration, and activity level.[34] In the present study, participants used their non-dominant arm in the exercise protocol, with the goal of avoiding excessive movement of the arm post exercise which might have led to recovery; this use of the non-dominant arm explains why the EX and CON arms were so different in PhA and the other impedance variables even at baseline. The dominant arm of an individual is frequently more muscular than the non-dominant arm, which would influence segmental PhA values, even at baseline measurements prior to any exercise.[18,19] The fluid shifts and alterations of impedance variables shown in previous literature were expected to occur in the present study, due to the muscle damage and expected subsequent shifts in fluid incurred from the exercise protocol.

With these functional physiological responses established, the primary outcome of interest, PhA, was evaluated in relation to these changes. It was expected that participants would have higher PhA values directly following the exercise protocol compared to pre-protocol measurements, as resistance exercise can move fluid into muscle tissue and cause cellular swelling in the working muscle, making the surrounding tissue more conductive in a BIA analysis. Further, inflammation due to EIMD causes imbalances between intra- and extracellular spaces, which heavily influence the hydration of the tissue and the capacity of the cell membrane, resulting in acute changes in PhA.[35] Instead of having higher values, almost all participants showed an acute decreased PhA value directly following the exercise protocol, similar to results found by Freeborn et al., (2020). Additionally, changes in PhA were not maintained over the three days;

most participants' PhA values returned to or neared baseline by the end of the study. This is not uncommon, as PhA is directly related to the inflammatory state of body tissues. Decreases in PhA tend to be more pronounced in individuals with higher levels of inflammation or cell damage due to the relationship that exists between PhA and inflammatory markers.[36] Despite the significant differences found in the other impedance variables, changes in PhA of the arm used in the exercise protocol were not pronounced enough or maintained long enough to reach statistical significance. There are a few possible explanations for this, most of which are likely due to the participants involved in the study; all the participants were considered trained and regularly participate in resistance training. This likely impacted their recovery capabilities, and with consideration to the repeated bout effect[1], they were less likely to experience DOMS and the symptoms of DOMS for prolonged periods. For some participants, the exercise was not difficult and may not have been enough stimulus to actually induce damage. Other participants found the exercise protocol very difficult, and still recovered well. The individual variability in PhA responses, responses to eccentric exercise, and general muscular recovery timelines likely played a large role in PhA values not changing significantly throughout the duration of the study.[1,3,37]

Due to the nature of the exercise protocol in the current study, and the existing relationships between EIMD, inflammation, swelling, and subsequent muscular soreness, it was anticipated that participants would display high levels of soreness and pain sensitivity following the exercise protocol. While no significant differences were found in either of the measures of muscular soreness, significant differences were found in the fluid compartments of the arms that participants used in the exercise protocol. Finally, subjective and perceptual markers of muscle damage were assessed to further contextualize the recovery response in participants. In this study, muscular soreness was evaluated using both a pressure-pain threshold test and a pain tolerance test. No significant differences found in either the pain tolerance or the soreness of the participants; most participants did anecdotally report feeling soreness in the arm used in the protocol in the days following the eccentric exercise bout, in addition to having increased (although not statistically significant) scores on the VAS for pain measurement. Lau et al,[37] found that muscular soreness and VAS scores peaked at 1-2 days post-exercise and slowly recovered to baseline levels at around 5 days following the initial exercise bout. A similar study investigating soreness following eccentric calf raises found muscular soreness first appeared around 24 hours after exercise, peaking 48 to 72 hours after exercise, and resolving around 96 hours after the initial exercise bout.[38] Results from the current study were similar; pain tolerance scores were lowest and VAS scores highest at the 24 and 48-hour marks following the exercise bout, although not statistically significant. Some participants noted soreness immediately following completion of the exercise protocol, and only a few reported feelings of little to no soreness at the 72-hour check-in. It was expected that there would be significant differences in pain threshold and pain tolerance at the 48 and 72-hour check-in visits, at the typical time frames in which DOMS peaks.[1,3,37] There was a moderately strong, positive relationship found between pain-pressure threshold values and MVIC values ($r= 0.509$, $p <0.001$); as participants recovered throughout the monitoring period, their soreness dissipated, and strength returned. Additionally, there was a weak negative relationship found between MVIC and VAS values ($r=-0.451$, $p< 0.001$), indicating that as strength returned, pain associated with muscular soreness was not as severe. It was expected that participants would undergo some degree of recovery throughout the monitoring period, and these relationships investigated support this.

Based on the results of the current study, more research needs to be conducted investigating the use of segmental PhA in monitoring muscular damage and recovery following an acute bout of muscle damaging exercise. The noted changes in PhA, while not significant, do indicate that PhA

can be impacted and altered by acute bouts of muscle damaging exercise; with a larger and more diverse sample size, it is possible that PhA would show significant changes pre- to post-exercise, and therefore, it should not be ruled out as a potential useful tool for monitoring muscular damage and recovery. As an established method for monitoring cellular health and inflammation in chronically ill populations,[39] the known relationship between PhA and inflammatory status serves as an important link to a potential relationship between PhA and exercise-induced inflammation and damage. Although the majority of current literature only suggests that PhA is affected by longer-term resistance training,[40] the results of the present study indicate a need for more research investigating PhA responses to acute bouts of exercise in order to find meaningful changes and differences.

The results of this study also suggest that PhA and muscular soreness are unrelated within the boundaries of the current research design. While there is no current literature suggesting that the two variables are related or investigating the two variables together, based on the relationship between inflammation, body water changes, and DOMS, it was anticipated that there would be some interaction between the two. Due to the lack of significant findings, it does not appear as though PhA has much use in monitoring muscle performance or muscle damage following an acute bout of eccentric exercise within the boundaries of this research protocol. More recent literature suggests that PhA may be a useful tool in monitoring overtraining syndrome in athletes,[35] but more research is needed. Regardless, PhA is still a useful variable to monitor, particularly in chronically ill individuals.[18,36,39]

There are multiple limitations to note in this study. Firstly, the sample size of this study was small, which significantly reduced the statistical power of this study. With greater statistical power, there may have been statistically significant changes in PhA values. A post-hoc power analysis indicates that sample size of 12 high-responders or 32 low or non-responders to eccentric exercise would be necessary to see meaningful changes; the sample size of 12, including several low-responders and one non-responder did not reach the calculated sample sizes. Although sex was recorded and is reported for descriptive purposes, the present study was not designed or statistically powered to detect sex-specific differences. The sample size was determined based on overall study aims rather than stratified analyses, and the unequal distribution of male and female participants further limits the ability to conduct meaningful between-sex comparisons. Therefore, sex-based analyses were not performed to avoid underpowered and potentially misleading inferences. Future investigations should be specifically designed and adequately powered to examine sex-specific responses to acute eccentric exercise, particularly given the potential for differential physiological adaptations.

Although significant soreness was expected, there are several possible explanations and potential limitations as to why this did not occur. Firstly, to be eligible for participation, participants had to be physically active and participate in resistance training at least three times a week. The more often an individual participates in a form of exercise, the less likely it will be that they experience DOMS as a result of an exercise bout of that type;[3] regular, high frequency and high intensity resistance training reduces the susceptibility of an individual to DOMS, per the repeated-bout effect.[3] Additionally, the participants were not monitored outside of their lab check-ins; outside of their lab visits, they were instructed to go about their days as normal, including eating, drinking, and moving as they normally would (although they were asked to avoid anything that may alleviate their soreness, such as medication and massage, as well as to avoid any excessive movement of the arm used in the protocol). Unmonitored lifestyle habits may have influenced

recovery rate and soreness.[11] Current literature on muscular soreness as a result of eccentric exercise suggests that pain associated with muscle damage may differ depending on how the muscle is assessed.[37] While it is important to assess pain at different points in the muscle, the central region of the biceps brachii can give an important look into muscular soreness because of eccentric elbow flexor actions. In the current study, the soreness was evaluated in the central region of the biceps brachii both before and after each MVIC measurement at all check-ins; had alternative locations of the biceps brachii been investigated, different results may have been found.[37]

In future studies, participants should be more closely monitored to improve the overall control of the study. This could be done by implementing more check-in visits, stricter guidelines for participants to follow for the duration of the monitoring period, having participants keep a food and drink log, and monitoring the hours of sleep participants get each night throughout the study. Food and drink intake, as well as sleep, would be quite important to monitor as these variables can have a large impact on inflammation, hydration, and consequently, PhA.[36] If this study were to be replicated, ideally, it should include a larger overall sample size, including more women and different ethnic groups, to further increase generalizability of data. Additionally, it would be beneficial to screen participants for responsiveness to eccentric exercise and/or group participants based on resistance training participation. Finally, the actual exercise protocol could be modified to be more impactful; instead of implementing the threshold of a 60% decrease in MVIC values, the threshold could be increased to 75-80%. By increasing the threshold, it would be more likely that participants would undergo significant muscle damage, resulting in more significant changes in PhA and muscular soreness, and potentially more likely to see changes in even the lowest responders to eccentric exercise.

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