Eccentric exercise slows in vivo microvascular reactivity during brief contractions in human skeletal muscle

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Eccentric exercise slows in vivo microvascular reactivity during brief contractions in human skeletal muscle. J Appl Physiol 119: 1272–1281, 2015. First published October 1, 2015; doi:10.1152/japplphysiol.00563.2015.—Unaccustomed exercise involving eccentric contractions results in muscle soreness and an overall decline in muscle function, however, little is known about the effects of eccentric exercise on microvascular reactivity in human skeletal muscle. Fourteen healthy men and women performed eccentric contractions of the dorsiflexor muscles in one leg, while the contralateral leg served as a control. At baseline, and 24 and 48 h after eccentric exercise, the following were acquired bilaterally in the tibialis anterior muscle: 1) transverse relaxation time (T2)-weighted magnetic resonance images to determine muscle cross-sectional area (mCSA) and T2; 2) blood oxygen level-dependent (BOLD) images during and following brief, maximal voluntary contractions (MVC) to monitor the hyperemic responses with participants positioned supine in a 3T magnet; 3) muscle strength; and 4) pain pressure threshold. Compared with the control leg, eccentric exercise resulted in soreness, decline in strength (~20%), increased mCSA (~7%), and prolonged T2 (~7%) at 24 and 48 h (P < 0.05). The BOLD response to a brief MVC was altered 24 and 48 h after eccentric exercise, such that time-to-peak (~35%, P < 0.05) and time-to-half-recovery (~23%, P < 0.05) were prolonged. The altered contraction-induced hyperemic response suggests slowed microvascular reactivity and altered matching of O2 delivery to O2 utilization within muscle tissue showing signs of muscle damage. These changes in microvascular regulation after eccentric exercise may impede rapid adjustments in muscle blood flow at exercise onset and during activities involving brief bursts of muscle activation, which may impair O2 delivery and contribute to reduced muscle function after eccentric exercise.

blood oxygen level dependent (BOLD); hyperemia; muscle damage

PHYSICAL ACTIVITIES THAT ARE unaccustomed and involve lengthening (i.e., eccentric) muscle contractions are known to induce structural changes in skeletal muscle, and result in a decline in force generating capacity and overall reduction in muscle function (5). This phenomenon is referred to as exercise-induced muscle damage, and is often documented by elevated concentration of intracellular proteins (e.g., creatine kinase or myoglobin) in blood plasma (5). A limitation of this approach is that plasma protein levels do not provide information about which muscle group (or groups) is affected by the exercise. In contrast, measures of muscle soreness, muscle pain sensitivity, and muscle strength comprise information regarding the effects of on distinct muscle groups. In addition, eccentric exercise is accompanied by processes that ultimately result in muscle swelling and edema, which can be localized to specific muscles and quantified on the basis of relative increases in muscle mass after eccentric exercise, the following were acquired bilaterally in the tibialis anterior muscle: 1) transverse relaxation time (T2)-weighted magnetic resonance images to determine muscle cross-sectional area (mCSA) and T2; 2) blood oxygen level-dependent (BOLD) images during and following brief, maximal voluntary contractions (MVC) to monitor the hyperemic responses with participants positioned supine in a 3T magnet; 3) muscle strength; and 4) pain pressure threshold. Compared with the control leg, eccentric exercise resulted in soreness, decline in strength (~20%), increased mCSA (~7%), and prolonged T2 (~7%) at 24 and 48 h (P < 0.05). The BOLD response to a brief MVC was altered 24 and 48 h after eccentric exercise, such that time-to-peak (~35%, P < 0.05) and time-to-half-recovery (~23%, P < 0.05) were prolonged. The altered contraction-induced hyperemic response suggests slowed microvascular reactivity and altered matching of O2 delivery to O2 utilization within muscle tissue showing signs of muscle damage. These changes in microvascular regulation after eccentric exercise may impede rapid adjustments in muscle blood flow at exercise onset and during activities involving brief bursts of muscle activation, which may impair O2 delivery and contribute to reduced muscle function after eccentric exercise.

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increase in BOLD signal intensity in T2-weighted images (11, 24, 41). A single contraction elicits a transient increase in BOLD signal intensity, which reflects that oxygen, spatially and temporally, is delivered in excess of the O₂ required to restore the small phosphocreatine breakdown during the brief contraction (41, 42). Because this phenomenon results primarily from an increase in oxygen saturation and blood volume in the smaller vessels, the time course of the BOLD response has been interpreted to reflect microvascular reactivity (39, 41).

Many activities involve brief bursts of muscle activity, which emphasizes the physiological significance of the ability to rapidly augment blood flow to match O₂ delivery to O₂ demand. So far, little is known about the effects of eccentric exercise on microvascular reactivity in human skeletal muscle. Therefore, the aim of this study was to examine in vivo microvascular function using BOLD MR imaging during brief maximal voluntary contractions of the dorsiflexor muscles before and after (24 and 48 h) eccentric exercise. It was hypothesized that the eccentrically exercised tibialis anterior (TA) muscle would exhibit an altered hyperemic BOLD response, specifically 1) increased time-to-peak (TTP), mirroring slowed vasodilatation; 2) lower peak magnitude, reflecting reduced total vasodilator capacity; and 3) prolonged time to half relaxation, indicative of altered matching of O₂ delivery to O₂ utilization in the exercised muscle tissue.

METHODS

Participants. Fourteen healthy young men (n = 7) and women volunteered to participate in the study. A preliminary screening session was used to confirm that participants were nonsmokers and not taking any medications or dietary supplements known to affect metabolism or blood flow. All participants were recreationally active but did not engage in strength training of the lower body. Regular physical activity did not exceed 3 h per week, which was verified by the short form of the International Physical Activity Questionnaire (8), and stored on a computer. The footplate device was built from nonmagnetic materials to allow force measures to be obtained while participants performed MVCs in the MR scanner.

Eccentric exercise protocol. The eccentric exercise protocol consisted of controlled lengthening contractions of the dorsiflexor muscles of the experimental leg (18, 19), which was randomized and counterbalanced such that half of the participants performed contractions with the right leg, whereas the other half used the left leg. Participant stood on a 13-cm-high platform placed 45 cm from a wall. The foot of the experimental leg was secured to a footplate that was attached to the platform via a hinge, allowing free dorsiflexion and plantarflexion. The palms of each participant’s hands were placed flat on the wall at shoulder level for support during the contractions. The nonexperimental leg (i.e., control leg) was lifted off the platform by flexing at the hip and knee, and thus transferring to single leg stance on the experimental leg side. Participants then performed a controlled plantarflexion of the foot and ankle (requiring lengthening of the TA muscle) until the footplate touched the floor. At this point, the control leg was extended until it was weight bearing and was used to assist in returning the participant to the initial starting position. This process was repeated 10 times per set separated by 30 s of rest, and continued until the participant was unable to perform controlled, lengthening contractions. Because the efficacy of this protocol varied among individuals (18, 19), participants performed between three and five sets of exercises.

Muscle soreness. To evaluate progression of soreness in the TA muscle of the experimental leg, participants filled out a modified Likert scale questionnaire (0 = no soreness, 6 = severe soreness) at baseline and every 12 h for the first 2 days after the eccentric protocol and then every 24 h for the following 4 days (18). In addition, a measure of pain pressure threshold (PPT) was obtained from the belly of the dorsiflexor muscle using a handheld ergometer (Somedic, Horby, Sweden) with a 1-cm² probe. The ergometer was oriented perpendicular to the muscle and pressure stimulation was gradually increased (30 kPa/s) until PPT was reached. Via a push button, participants were instructed to indicate PPT when pressure sensation became painful. The PPT procedure was repeated twice at baseline, and again 24 h post and 48 h post. The averages of these measurements were used for further analyses.

Magnetic resonance imaging. All MR imaging acquisitions were performed using a standard 14-cm-diameter GE clinical extremity coil on a 3T Signa GE imaging system (GE Healthcare, Milwaukee, WI). Participants were positioned supine in the MR scanner with the foot secured to the force recording apparatus, as described above. The extremity coil was positioned around the lower leg with the belly of the dorsiflexor muscles in the center of the coil. This position was marked with a pen on the participant’s leg and used for identical positioning during subsequent sessions. To limit motion artifact and participant discomfort during the MR session, padding was placed around the leg and knee. Before the first MR scan in each session, participants rested supine in the scanner for ~15 min.

At the start of each MR session, gradient echo images were acquired in three planes, and all subsequent images were acquired from the slice location corresponding to the center of the coil. T2-weighted axial images (TR, 1,500 ms; TE, 24 ms; number of echoes, 4; FOV, 18 cm; slice thickness, 10 mm; slice gap, 1 mm; acquisition matrix, 320 × 224; NEX, 1) were acquired to determine CSA and T2 of the TA muscle using commercial software (AW server 2.0; GE Healthcare). In brief, mCSA was determined by manually
outlining the TA muscle compartment, and the transverse relaxation time was determined using T2 mapping in a large region of interest (ROI) within the TA compartment, excluding resolved vessels and subcutaneous fat. These analyses were carried out by the same investigator, who was blinded to the identity of the data.

**Assessing microvascular function.** Before assessing microvascular function using an MR BOLD protocol adapted from previous studies (33, 41), participants performed three MVCs of 3- to 5-s duration in the scanner to determine muscle strength of that day. To allow recovery, participants rested 1 min between each of these contractions. Then BOLD, one-shot, gradient echo images (TR, 1,000 ms; TE, 40 ms; FOV, 18 cm; slice thickness, 10 mm; acquisition matrix, 64 × 64; NEX, 1; flip angle, 90°) were acquired continuously for 7.5 min (i.e., 450 images) during which time participants performed a brief MVC (a total of seven contractions) every 60 s. Each participant received verbal cues and encouragement by the same investigator through all contractions to ensure consistent timing and maximal effort of the contractions. The order of MR procedures was balanced by leg, such that half of the participants started the MR procedures with the control leg, whereas the other half started the MR procedures with the experimental leg.

The force data acquired during the brief contractions were analyzed to determine peak force, time-tension-integral (TTI), and duration of the contraction using custom written MatLab program (Mathworks, Natick, MA). Similarly, a custom written MatLab program was used to analyze the BOLD images. Specifically, a manually drawn ROI that comprised the majority of the TA compartment and excluded bone, subcutaneous fat, and resolved vessels was stored, and the signal intensity was extracted within the ROI for each of the 450 images. The data were temporally aligned and averaged across all seven contractions to create an individual 60-s time course for BOLD signal intensity (Fig. 1). This time course was used to determine peak change in BOLD signal intensity (relative to minimum signal intensity post contraction) and TTP (from end of contraction) and time to half recovery of the BOLD transient.

**Statistical analyses.** Statistical analyses were performed using SAS software (SAS Institute, Cary, NC). Three-way (sex, leg, session) repeated-measures ANOVA were used to test gender-based differences in any markers of muscle damage. There were no significant effects of sex or any sex-by-leg or sex-by-session interactions. Therefore, data for subsequent analyses were collapsed across sex. Two-way (leg, session) repeated-measures ANOVA models were used to examine the effects on eccentric exercise on measures of muscle strength, mCSA, T2, PPT, force data from the BOLD protocol, and measures of microvascular function in the experimental leg and control leg (leg), across the three (baseline, 24 h, 48 h) testing sessions (session). Significant interactions effects were further explored with post hoc pairwise comparisons using Tukey’s procedure correcting for multiple comparisons. Muscle soreness (Likert scale) was analyzed using one-way repeated-measures ANOVA with Tukey’s post hoc tests. Associations between markers of muscle damage and changes in measures of microvascular function were assessed via Pearson’s product-moment correlation coefficient. All data are presented as means and standard deviation (SD) with statistical significance being accepted when \( P < 0.05 \). As measures of absolute reliability, coefficient of variation (CV) and intraclass correlation coefficients (ICC)

![Fig. 1. Time course of signal intensity changes in tibialis anterior muscle in one representative participant, reflecting the hyperemic response to brief, maximal contractions. The figure illustrates signal intensity changes for each of the seven contractions at baseline (A) and 48 h after eccentric exercise (B), and the response averaged over all seven contractions at baseline (C) and 48 h after eccentric exercise (D). Spikes in signal intensity (every 60 s) coincide with contractions and are due to changes in signal saturation when the muscle contracts and moves in the imaged slice.](image-url)
RESULTS

One of the 14 volunteers did not develop soreness or signs of damage in the TA muscle after eccentric exercise, as indicated by Likert scores equal to 0 (i.e., no soreness) and confirmed by no apparent decline in muscle strength. Therefore, the data from this participant are not included in the analyses. Participant characteristics are presented in Table 1.

Muscle soreness and damage. Likert scores from the TA muscle of the experimental leg displayed a typical temporal profile for delayed onset muscle soreness with peak levels between 24 h and 48 h, and soreness values returning to baseline levels after 120 h (Fig. 2). ANOVA revealed significant main effects by leg \((P < 0.001)\) and session \((P < 0.002)\) but no interaction effect \((P > 0.89)\) for PPT. Relative to baseline, PPT was reduced to 85.2 ± 20.6\% (24 h) and 86.9 ± 24.6\% (48 h) in the experimental leg, which was not different from changes in PPT in the control leg \((86.0 ± 15.2\% \text{ and } 90.9 ± 22.3\%, \text{ respectively})\). There were significant main effects by leg \((P < 0.001)\) and session \((P < 0.04)\) and an interaction effect \((P < 0.02)\) for muscle strength. Compared with baseline, muscle strength was reduced by ~20\% at 24 h \((P < 0.01)\) and 48 h \((P < 0.04)\) in the experimental leg, whereas muscle strength was maintained in the control leg (Fig. 3).

There were significant main effects by leg \((P < 0.001)\) and session \((P < 0.01)\) and an interaction effect \((P < 0.04)\) for T2 (Fig. 3). Compared with baseline, T2 was elevated at 24 h \((P < 0.01)\) and 48 h \((P < 0.02)\) in the experimental leg, with no changes in the control leg. Similarly, there were significant main effects by leg \((P < 0.001)\) and session \((P < 0.01)\) and an interaction effect \((P < 0.02)\) for mCSA, such that mCSA in the experimental leg, but not in the control leg, was increased at 24 h \((P < 0.004)\) and 48 h \((P < 0.02)\) compared with baseline (Fig. 3).

Contractions during the BOLD protocol. ANOVA revealed no significant main effects or interaction effect on duration and or contraction level (% MVC) during the brief contractions used to evoke the BOLD responses (Table 2). However, there were main effects by leg \((P < 0.004)\) and session \((P < 0.005)\) and an interaction effect \((P < 0.008)\) for TTT. Compared with baseline, TTT was unchanged in the control leg, but reduced in the experimental leg at 24 h \((P < 0.002)\) and 48 h \((P < 0.004)\), consistent with the overall decline in muscle strength at these time points.

Microvascular function. Figure 1 shows a representative example of the BOLD responses acquired during a sequence of seven brief, maximal contractions obtained from the TA muscle in the experimental leg at baseline and 48 h after the eccentric exercise. Minimal BOLD responses precluded analyses of temporal hemodynamics in one participant, such that these analyses are based on data from 12 participants. In addition, BOLD data at 24 h exclude one participant (control and experimental leg) due to technical problems. ANOVA revealed main effects by leg \((P < 0.006)\) and session \((P < 0.008)\) and an interaction effect \((P < 0.02)\) for TTP of the BOLD response (Fig. 4). Compared with baseline, TTP was prolonged at 24 h \((33\%, P < 0.01)\) and 48 h \((36\%, P < 0.006)\), with no changes in the control leg. There were significant main effects by leg \((P < 0.001)\) and session \((P < 0.02)\) and an interaction effect \((P < 0.009)\) for time to half recovery of the BOLD response (Fig. 4). Specifically, compared with baseline, time to half recovery was prolonged at 24 h \((25\%, P < 0.005)\) and 48 h \((21\%, P < 0.01)\) in the experimental leg with no changes in the control leg. There were no significant main effects or interaction effects for peak magnitude of the BOLD response (Fig. 4). The CV of peak magnitude, TTP, and time to half recovery for the control leg across the three testing days was \(18.2\%, 11.4\%\), and \(7.9\%\), respectively. The ICC\((3,1)\) of peak magnitude, TTP and time to half recovery for the control leg, across the three testing days, was \(0.26, 0.29, \text{ and } 0.20, \text{ respectively}\

DISCUSSION

The primary result of this study is the altered contraction-induced hyperemic response of the microvasculature following
unaccustomed, eccentric exercise. Specifically, despite no change in peak magnitude, time to peak and time to half recovery of the BOLD response to brief, maximal contractions were prolonged at 24 and 48 h after eccentric exercise. These results indicate that a moderate degree of exercise-induced muscle damage slows vasodilation of the microvasculature and alters the matching of O2 delivery to O2 utilization in response to brief contractions. Thus these findings suggest that eccentric exercise may reduce the ability to rapidly augment blood flow (to match O2 delivery to O2 demand) at exercise onset and during activities with intermittent muscle activity bursts, which ultimately may impair muscle function.

Prolonged TTP after eccentric exercise. Monitoring the hyperemic responses to brief contractions using MR BOLD imaging provided high temporal and spatial resolution, and allowed an examination of distinct components of the hyperemic response in the microvasculature of eccentrically exercised muscle tissue. Furthermore, this approach eliminated the influence of continuous stimulation of the vasculature and changes in muscle oxidative metabolism, and thus helped us

Fig. 3. Top: representative anatomic T2-weighted images acquired from the experimental leg and the control leg in one participant during the MR imaging protocol 48 h after eccentric exercise. Bottom: markers of muscle damage obtained from the tibialis anterior muscle (outlined) in the experimental leg (eccentric, filled bars) and control leg (control, open bars). Muscle strength, muscle cross-sectional area, and T2 values are illustrated. Data are from 13 participants and presented as means ± SD. *Significant differences (P < 0.05) between baseline and 24 h or 48 h post hoc (using Tukey’s procedure).
specifically examine contraction-induced microvascular reactivity (3, 6, 9). Prior to the eccentric exercise, characteristics of the BOLD response were comparable to results from previous studies that used a similar approach to examine microvascular function in the TA muscle of healthy, young adults (33, 39, 41, 42).

In the present study, prolonged TTP (−35%) in response to brief contractions was found at 24 and 48 h after eccentric exercise. Consistent with our results showing prolonged TTP after eccentric exercise, lengthening contractions of the rat soleus muscle have been shown to attenuate dilation of microvessels in response to adenosine, a potent metabolic dilator (22). In addition, Kano and colleagues (25) reported an accelerated fall in microvascular oxygen pressure (−40%) at the onset of electrically stimulated contractions in rat spinotrapezius muscle 24 and 72 h after downhill running, suggesting impaired microvascular hemodynamics. Although Kano et al. (25) examined changes in microvascular hemodynamics in response to continuous, stimulated muscle activity, the present study extend these results by showing slowed microvascular reactivity in response to single, brief muscle contractions. The present study thus provides novel evidence of blunted contraction-induced microvascular reactivity after eccentric exercise in human skeletal muscle.

Slowed vascular reactivity has been demonstrated in elderly and patients with peripheral artery disease or diabetes, and interpreted as evidence of impaired vascular function (3, 15, 34, 44). Using BOLD imaging, slowed TTP after reactive

### Table 2. Muscle contraction parameters from magnetic resonance BOLD protocol

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>24 Hours</th>
<th>48 Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscle strength, MVC, N</td>
<td>Control</td>
<td>286.7 ± 109.9</td>
<td>289.3 ± 110.4</td>
</tr>
<tr>
<td></td>
<td>Eccentric</td>
<td>263.7 ± 100.4</td>
<td>203.4 ± 83.7*</td>
</tr>
<tr>
<td>Duration of contraction, s</td>
<td>Control</td>
<td>1.93 ± 0.21</td>
<td>1.87 ± 0.12</td>
</tr>
<tr>
<td></td>
<td>Eccentric</td>
<td>1.92 ± 0.20</td>
<td>1.94 ± 0.17</td>
</tr>
<tr>
<td>Peak force, % MVC</td>
<td>Control</td>
<td>94.0 ± 4.7</td>
<td>92.1 ± 9.7</td>
</tr>
<tr>
<td></td>
<td>Eccentric</td>
<td>96.4 ± 8.4</td>
<td>93.2 ± 13.3</td>
</tr>
<tr>
<td>TTI, N/s</td>
<td>Control</td>
<td>277.8 ± 102.3</td>
<td>271.5 ± 105.8</td>
</tr>
<tr>
<td></td>
<td>Eccentric</td>
<td>290.7 ± 116.6</td>
<td>206.9 ± 88.2*</td>
</tr>
</tbody>
</table>

Data are from 13 participants and presented as means ± SD. *Significant difference post hoc (P < 0.05) (Tukey’s procedure) between baseline and 24 h or 48 h after eccentric exercise. BOLD, blood oxygen level dependent; TTI, time tension integral; MVC, maximal voluntary contraction.

![Fig. 4. Peak, time to peak, and time to half recovery of the BOLD response are presented for the experimental leg (eccentric, filled bars) and control leg (control, open bars). Data are from 12 participants and presented as means ± SD. *Significant differences (P < 0.05) between baseline and 24 h or 48 h after eccentric exercise post hoc (using Tukey’s procedure).](japplphysiol.org)
Hyperemia was reported in the TA muscle of patients with peripheral arterial occlusive disease compared with age-matched controls, supporting the notion that prolonged TTP of the BOLD response reflects microvascular dysfunction. Although the results of the present study demonstrate slowed contraction-induced hyperemic response, the functional significance of a 35% decline in microvascular reactivity is unclear. Various vasodilatory signals may compensate for impaired microvascular responsiveness, and thus preserve blood flow during continuous muscle activity. However, many activities are characterized by short bursts of muscle activity, and the slowed hyperemic response after eccentric exercise may thus indicate reduced ability to rapidly augment blood flow to match O2 delivery to the metabolic demand in the exercising muscle, which highlights the physiological and clinical relevance of this result.

Mechanisms for rapid vasodilation. The increase in blood flow in response to a single, brief contraction is thought to be due to local vasodilation. However, the mechanisms for the rapid vasodilation have not been fully elucidated, yet mechanical factors as well as release of vasodilators from contracting skeletal muscle cells and the endothelium have been proposed to contribute (4, 7, 10). Notably, most studies examining the underlying mechanisms of the hyperemic response to brief single contractions have been conducted in the upper extremity, which questions the extrapolations of findings in the arms to the vasculature in the lower leg (10). However, a recent study reported similarities between the hyperemic responses to single contractions in the brachial and femoral arteries, suggesting similar vascular control during brief contractions in the upper and lower extremities (10). In the present study, participants were positioned supine in the MR scanner while they performed brief contractions, which prevented an increase in hydrostatic pressure in the lower leg and thus diminished a possible muscle pump contribution to the hyperemic response (10). Collectively, these results suggest that the BOLD response to brief contractions, as used in the present study, is influenced primarily by factors related to function of the endothelium and smooth muscle in the microvasculature.

Inflammation and effects on vasodilation. Strenuous exercise involving eccentric muscle contractions is associated with inflammation and elevated oxidative stress (23, 40), which acutely can impair nitric oxide (NO)-mediated vasodilator function (21). There is evidence to suggest that even low levels of oxidative stress can contribute to altered vascular control in sedentary young adults (32). Specifically, scavenging of reactive oxygen species via enhancing antioxidant capacity by intra-arterial infusion of ascorbic acid resulted in increased vascular responsiveness to acetylcholine and nitroprusside, endothelial and vascular smooth muscle agonists, respectively (32). Thus the inflammatory processes that accompany eccentric exercise may lower NO bioavailability and impair endothelial function and vascular smooth muscle responsiveness, which may contribute to delayed onset vasodilation of the microvasculature. Notably, the present study was not designed to investigate the contribution of various mechanisms to the altered BOLD response after eccentric exercise. Therefore, future studies are warranted to investigate the underlying mechanisms for blunted microvascular reactivity after eccentric exercise.

Prolonged time to half recovery of BOLD response. Although peak magnitude of the BOLD response to brief, maximal contractions has been reported to be threefold greater in trained compared with untrained young adults (42), the unaltered peak magnitude in the present study suggested no apparent decline in overall vasodilator capacity to a brief contraction after eccentric exercise. However, the time to half recovery of the BOLD response was prolonged (~23%) 24 and 48 h after eccentric exercise. Considering that the BOLD signal is influenced by hemoglobin saturation levels and blood volume (41, 44), the prolonged hyperemic response to a brief contraction can occur as a consequence of various scenarios resulting in an increased proportion of oxygenated hemoglobin and/or an increase blood volume after contraction (11, 41).

The prolonged BOLD response to a brief contraction in the present study is consistent with that of previous studies, providing evidence of an increased ratio of O2 delivery to O2 utilization during continuous muscle activity after eccentric exercise (13, 29). Davies et al. (13) monitored the dynamic balance between O2 delivery and O2 utilization in human vastus lateralis muscle during rest-to-exercise transitions, before and 48 h after eccentric exercise. The kinetics of deoxygenated hemoglobin, measured by near-infrared spectroscopy, was slowed by ~30%, whereas the kinetics of pulmonary O2 uptake (used as a proxy of muscle O2 utilization) was maintained, suggesting an increased ratio of O2 delivery-to-O2 utilization in the exercised muscle. The authors interpreted these results to suggest that an increase in local muscle blood flow was required to maintain muscle O2 kinetics after eccentric exercise (13). Similarly, Laaksonen et al. (29) reported an increase in local blood flow, measured by positron emission tomography, during submaximal exercise, despite no change in pulmonary O2 consumption at 72 h after eccentric exercise. A possible explanation for the apparent increase in O2 delivery to O2 utilization ratio could be diminished extraction of O2 in muscle tissue affected by eccentric exercise (12, 25). In contrast, Ahmadi et al. (1) reported faster deoxygenation of hemoglobin during sustained, submaximal MVC after an exhaustive session of downhill walking. Assuming impeded blood flow during sustained isometric contractions, faster O2 deoxygenation indicates greater muscle O2 consumption after muscle-damaging exercise. Although muscle damage induced by neuromuscular electrostimulation has been shown to result in slowed phosphocreatine recovery, which is
indicates of impaired mitochondrial function (17), other studies have reported preserved mitochondrial function after moderate degree of exercise induced muscle damage (12, 46), suggesting that eccentric exercise may not compromise muscle oxidative function per se.

**Experimental considerations.** An inevitable consequence of exercise induced muscle damage is a decline in muscle strength (5, 30). Consistent with this notion, the eccentric protocol used in the present study resulted in a modest (∼20%) decline in muscle strength at 24 and 48 h after exercise. Force output from the muscle is regulated by recruitment and rate coding of motor units, and studies in the TA muscle of young adults have suggested that all motor units are recruited by 60–70% MVC (14). These results suggest that the brief, maximal contractions used to evoke BOLD responses in the present study recruited all TA motor units, both before and after eccentric exercise. This is important because the magnitude of muscle arteriolar vasodilation in response to a single contraction is proportional to the number of recruited motor units (45). Consistent with the assumption of activation of all TA motor units, no change in peak magnitude of the BOLD response was found after eccentric exercise. Similarly, Wigmore and colleagues (47) monitored the hyperemic responses to a series of brief isometric contractions of the dorsiflexor muscles, ranging from 10% to 100% MVC, and showed a plateau in the postcontraction hyperemic response at 60% MVC. Together, these results indicate that the modest decline in muscle strength at 24 and 48 h postexercise did not influence the stimulus for vasodilation to brief maximal contractions, and consequently the interpretation of the BOLD responses. Notably, Meyer and colleagues (33) showed lower peak BOLD during 50% MVC compared with MVC, providing some evidence that force production influences BOLD magnitude. Thus the small sample size may have concealed a possible decline in peak BOLD in response to lower force production (20%) after eccentric exercise. However, if anything, lower force output during the brief contractions would result in shorter TTP (37) and shorter time to half recovery (3, 9) of the hyperemic response, which emphasize the physiological significance of our results.

Although no direct evidence of muscle damage (i.e., muscle biopsy) was obtained, compelling evidence indicates that the eccentric exercise protocol resulted in damage localized to the TA muscle. Specifically, in agreement with results from previous studies that have used a similar protocol, a decline in strength of the dorsiflexor muscles was found (19). These findings were further extended by increased mCSA and prolonged T2 at 24 and 48 h after exercise. Several studies have shown prolonged muscle T2 after eccentric exercise, and reported correlations between T2 and ultrastructural changes as well as plasma levels of intracellular proteins (16, 30, 31, 35). Furthermore, soreness ratings from the TA muscle, evaluated by the Likert scale, displayed a typical temporal profile for delayed onset muscle soreness with peak soreness levels 24 and 48 h after exercise, matching the time points for measurements of microvascular function using BOLD MR imaging. However, the decrease in PPT in the experimental leg was not different from the change in PPT in the control leg, suggesting that the protocol did not develop hyperalgesia in the eccentrically exercised muscle. The link between muscle damage and altered microvascular function was emphasized by a significant correlation between prolonged TTP and the decline in muscle strength at 48 h after eccentric exercise. In contrast, prolonged T2 and Likert scores were not significantly correlated with longer TTP, highlighting the intricate and complex interaction between indices of muscle damage and microvascular function. Notably, the eccentric protocol used in the present study elicited relatively small changes in markers of muscle damage, muscle pain sensitivity, and measures of microvascular function, which will limit the ability to establish significant associations, particularly in combination with a relatively small sample size. Although gender differences in exercise-induced muscle damage have previously been reported, no gender-based differences were found in any markers of muscle damage. It is possible, however, that potential differences between genders were masked due to the small sample size used in the present study. Whereas the CVs of BOLD parameters in the control leg across testing days were relatively good (7–18%), ICCS(3,1) showed poor absolute reliability (0.40). Although there was no effect of time on the BOLD response in the control leg, it is possible that systemic effects (due to the eccentric exercise) influenced measures of absolute reliability because these measurements were acquired across all three testing days.

The MR BOLD technique used to evaluate microvascular function in the present study does not allow absolute quantification of perfusion or blood flow. However, a significant strength of this noninvasive methodology is the high temporal and spatial resolution of the acquired MR images. Specifically, the temporal resolution of the BOLD response captures distinct components (i.e., time to peak, peak magnitude, and time to half recovery) of the hyperemic response to brief contractions (33, 39, 41), which is essential when examining microvascular reactivity. In addition, the spatial resolution of the MR images allowed us to monitor the hyperemic response in a large, well-defined proportion of the TA muscle, and as such is representative of the majority of the muscle tissue involved in the eccentric exercise. These features of the BOLD method are critical in monitoring skeletal muscle hyperemia, because heterogeneity exists within muscle tissue, with respect to dynamics of oxygenation and distribution of damaged tissue (13, 28, 30).

**Conclusion.** These results show that eccentric exercise alters the hyperemic response of the microvasculature to brief muscle contractions. Specifically, time to peak and time to half recovery of the BOLD response were both prolonged at 24 and 48 h after eccentric exercise, suggesting slowed microvascular reactivity and altered matching of O2 delivery to O2 utilization in muscle tissue showing signs of a moderate degree of damage. Such changes may hinder rapid adjustments in blood flow to support O2 delivery at exercise onset and during brief bursts of muscle activity, which underlines the physiological and clinical relevance of these results.

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**DISCLOSURES**

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AUTHOR CONTRIBUTIONS


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