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Age Reduces Microvascular Function in the Leg Independent of Physical Activity

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Abstract

The microvasculature is critical in the control of blood flow. Aging and reduced physical activity may both decrease microvascular function.

Purpose—The primary aim was to evaluate the influence of age on microvascular function in adults with similar physical activity levels (PA). Secondary aims were to assess the reliability of muscle functional MRI in older adults and the relationship between physical activity and microvascular function in older adults.

Methods—Microvascular BOLD responses were measured in young adults (YA, $n=12$, 21 ± 1 ($\pm$ SD) years old, $PA=239\pm73\times10^3$ counts/day) and older adults (OA, $n=12$, 64 ± 4 years old, $PA=203\pm48\times10^3$ counts/day). Functional MR images (3T, echo planar blood-oxygen-level dependent (BOLD)), of the leg were acquired following brief (1s) maximal voluntary isometric contractions. Test-retest reliability of BOLD responses and the Pearson correlation between peak BOLD and PA was assessed in a group of older adults (OA-r) with a broad range of PA (66 ± 5 years old, $n=9$, PA range = 54×10^3 count/day to 674×10^3 counts/day).

Results—Peak BOLD microvascular responses were reduced for OA compared to YA. OA peak BOLD was 27% lower in the soleus (OA: $3.3\pm0.8\%$ vs. YA: $4.5\pm1.4\%$ YA, $p=0.017$) and 40% lower in the anterior compartment ($1.6\pm0.6\%$ OA vs. $2.7\pm1.1\%$ YA, $p=0.006$). Coefficient of variation was 8.6% and 11.8% for peak BOLD in the soleus and anterior compartment, respectively, with an intraclass correlation of 0.950 for both muscle regions. The correlation between peak BOLD and PA was $r=0.715$, $p=0.030$.

Conclusions—Aging was associated with reduced microvascular function in leg muscles, independent of physical activity. The findings also revealed good reliability for BOLD MRI in older adults for the soleus and anterior compartment muscles.

Keywords

Hemodynamic response Muscle BOLD; Functional MRI; Aging; Reliability; Exercise

Introduction

Microvascular function plays a pivotal role in blood flow regulation and muscle perfusion during exercise. Microvascular function is important because the increase in blood flow during the initial phase of exercise is controlled by rapid vasodilation of the terminal arterioles within the microcirculation (15, 25, 42). Aging has been associated with declines in microvascular function. For example, arteriole vasodilatory capacity and rate are reduced with age in rodents (3, 18). Recently, Park et. al, showed an age related reduction in vasodilatory capacity in small arteries (500 μ m in diameter, feed artery) supplying human skeletal muscle (28). In addition capillary density is also reduced in chronic disease (11, 31) and aging (13, 14). We have previously shown an inverse relationship between age (19–58 years old) and microvascular function of the anterior compartment (AC) using MRI blood oxygen-level dependent (BOLD) (37). In agreement, contraction mediated large artery flow (rapid onset vasodilation) with brief contraction is reduced in elderly adults in the brachial and femoral artery (4, 17). Reduced microvascular function or structure may contribute to altered perception of physical work and reduced physical function for many older adults. In this context, low capillary density was associated with reduced walking speed in older adults (2) and reduced walking time in patients with peripheral arterial disease (31) supporting a role for the microvasculature in functional performance.

Functional MRI BOLD imaging of skeletal muscle has been used increasingly over the last decade to examine peripheral microvascular function (23, 37, 41). Skeletal muscle BOLD responses arise largely from changes in blood volume and oxygenation from small veins, i.e. those that cannot be resolved in MRI images (22, 24, 40). Reduced BOLD magnitude or prolonged BOLD time courses have been reported in obesity (32), peripheral arterial disease (10), and diabetics with microvascular complications (37). Muscle BOLD responses are also remarkably higher in young, endurance trained adults compared to sedentary adults (40, 41) highlighting the influence of physical activity on peripheral vascular function. While previous data reported reduced skeletal muscle BOLD responses in older adults (34), it is unclear if the decline is due to aging *per se* or reduced physical activity.

This study aimed to evaluate age related differences in microvascular function in the anterior and posterior leg muscles. First, repeated testing of older adults (OA-r) with a broad range of physical activity (PA) was done to assess the reliability of BOLD responses and to assess the relationship between PA and BOLD responses. Next, BOLD responses were assessed in a group of young (YA) and older adults (OA) with matched PA. The primary hypothesis was that older adults have reduced peak BOLD microvascular responses in the leg following single brief contraction compared to young adults in groups closely matched for PA.

Materials and Methods

Subjects

Reliability—Nine older adults (1 male, ages 60–75 yrs) were recruited to determine test-retest reliability of muscle BOLD in older adults (OA-r). Participants with a broad range of PA level were invited to participate (sedentary - vigorous physical activity). Testing was done on two separate days (visit 1 and visit 2) separated by approximately one week. OA-r

subjects not performing vigorous physical activity (n=7) were considered for the age comparison study.

Age comparison study—For the main age group comparison study, 14 young adults (YA, 4 males, ages 18–35 yrs) and 15 older adults (OA, 3 males, ages 60–75 yrs) were recruited from the Lansing Community. YA were recruited that were not participating in any formal aerobic exercise training; most were college students who walked to class. Older adults with similar reported activity were recruited. Exclusion criteria for all subjects included diabetes, heart disease, peripheral vascular disease, and stroke. Subjects with ferrous implants or metal implants in the leg or knee were excluded. In addition, smokers and young subjects with a family history of diabetes were excluded. All participants provided written informed consent prior to participation. This research was approved by the Human Research Protection Program at Michigan State University.

Familiarization visit—An initial laboratory visit was done to assess baseline characteristics and to familiarize participants with the exercise ergometer. Height, weight, resting heart rate, and resting blood pressures were measured. Seated blood pressure was measured in the brachial artery using a standard arm blood pressure cuff, a sphygmomanometer and stethoscope. Supine ankle and brachial blood pressures were measured in the brachial, posterior tibial and dorsalis pedis arteries with a Dopplex D900 portable hand-held Doppler ultrasound. Ankle-brachial index was calculated (average of leg artery pressures/arm artery pressure) for both right and left sides; the average of both sides is reported. Blood pressure was measured to rule out uncontrolled high blood pressure 150 mmHg (OA), 140mm Hg (YA) mmHg systolic and 90 mmHg diastolic (all subjects). ABI was determined to rule out peripheral artery disease (ABI 0.90 in either leg).

Next, the subject lay supine with slight knee flexion (~5°) on a mock MRI table with the dominant foot placed into a custom-built ankle ergometer. Velcro straps were placed over the midfoot and forefoot. In addition, a 14-inch wide GE Velcro security strap was placed around the torso and hips to minimize movement of the body away from the footplate. Ankle dorsiflexion (DF) was done with the ankle at 125° and plantar flexion (PF) was done with the ankle fixed at 115°. These angle settings were selected based on the design of the ergometer. First, the subject practiced ~5 maximal contractions held for 2–3 seconds. The subject then performed a short practice test of single brief maximal contractions (1s) every 30 seconds with a visual cue for the timing of the contractions. This was done for DF and PF. A strain-gauge force transducer (Interface, model SSM-EV-250, Scottsdale, AZ) was mounted to the underside of the footplate and force was digitized (DATAQ Instruments, model DI-195B, Akron, OH), sampled at 120 Hz, and recorded on a personal computer. Subjects were given a physical activity monitor, ActiGraph GT1M, to wear at the hip for seven days. The accelerometer measures changes in acceleration in an intensity-dependent manner at 30 samples/s and records the accelerations as counts which are summed and stored over user defined time periods.

MRI visits—On a separate day, subjects had an MRI after an overnight fast (> 8 hours). Subjects were asked to refrain from aspirin, statins (OA: n=3, OA-r: n=2) and pain medications 12 hours prior to testing and to avoid exercise for 24 hours prior to testing.

Subjects taking blood pressure medications took them as normally prescribed (OA: n=3, OA-r: n=2). Blood was drawn by venipuncture to evaluate glucose, insulin, lipids and C-reactive protein (CRP). The serum was analyzed through Sparrow Laboratories using standard enzyme procedures with spectrophotometry (glucose, lipid panel), fluorescent polarization immunoassay (CRP), and chemiluminescence (insulin). Blood analyses were done to characterize the subjects and ensure they did not have elevated fasting glucose (< 110 mg/dL), elevated fasting insulin (< 30 μ IU), elevated markers of inflammation (CRP < 1.0 mg/dL), or high cholesterol (LDL < 160 mg/dL).

MRI images and spectra (MRS) of the lower leg were acquired on a GE Excite 3T system. Subjects lay supine on the MRI table. The subject's leg was placed in an 8-channel transmit/receive extremity coil. Support padding was placed around the leg and knee for comfort and to reduce motion. The subject was again instructed on ergometer use and performed ~5 practice maximal voluntary isometric contractions (MVCs) for 2–3 seconds, each separated by 1 minute. Each subject had a minimum of 20 minutes of supine rest prior to the target BOLD scans. Anatomical images (axial fast spin echo, TR/TE=600/12.4ms, 10mm slice, 5mm separation, 256 $\times$ 192 matrix, FOV=16) were acquired to quantify average muscle size and to prescribe the imaging slice for BOLD MRI. The subject then performed 1s MVCs during BOLD MRI; an echoplanar BOLD sequence (Gradient Echo, TR/TE = 1000/40, 64 $\times$ 64 matrix, FOV=16) of the slice with the largest area of target muscle was used to evaluate microvascular function. Visual cues for the timing of contractions ("Rest", "Ready", "PUSH" or "PULL") were displayed to the subject on the face of the magnet bore. For the first exercise protocol, the subject performed five DF MVCs with each contraction separated by 60 sec. Next, the subject performed five PF MVCs with each MVC separated by 120 sec. A longer recovery time was deemed necessary for PF during pilot data collection. Scans were repeated when subjects had significant motion, muscle twitching or low force (approximately $< 75\%$ MVC) during scanning. Last, a gated ^{31}P MRS protocol using single brief contractions (2s), similar to those in the BOLD protocol, was performed to evaluate oxidative capacity of the AC as previously described (36). A small 5 $\times$ 8 cm elliptical ^{31}P MRS surface coil was secured over the largest portion of the AC with a Velcro strap to acquire ^{31}P spectra during a DF exercise protocol. A small phantom was placed in the middle of the coil to ensure that the coil was centered on the largest area of the AC based on a localizer and a single slice T1-weighted scan. Single shot phosphorus spectra were acquired throughout the protocol (51.7 MHz, 1024 complex points, sweep width 2500 Hz, 30–90 degree pulse width at coil center, TR=4s). The protocol included an initial 1 minute of rest followed by twenty 2-s dorsiflexion MVCs each separated by 40 s of rest/recovery.

Subjects were excluded from either study if venous occlusion and subsequent filling occurred during BOLD MRI as venous filling grossly enhances BOLD (9). Venous occlusion was identified during post-processing when the BOLD signal failed to reach a steady state between contractions. For young females, the MRI visit was scheduled during the early follicular phase of the menstrual cycle.

Analyses—For muscle BOLD, the regions of interest (ROI) were selected in areas with homogenous signal, excluding areas that contained large, visible veins. The soleus (SOL) and medial gastrocnemius (MG) were the two ROIs selected from the PF protocol. The

entire AC was analyzed as a single ROI from the DF protocol which primarily included the tibialis anterior and extensor digitorum longus muscles, both of which have an action of ankle DF. Peak BOLD magnitude and time to reach peak BOLD (TTP) were measured following each MVC. The BOLD signal half recovery time was also measured. The BOLD responses that corresponded with the highest force contractions ($\pm 85\%$ MVC) without subject motion were averaged together, typically representing 2–3 post-contraction responses. The peak BOLD response was normalized to baseline for each contraction. TTP BOLD response was determined as the time between the start of contraction and the peak BOLD response to one decimal place. MRS data were analyzed with jMRUI software (Version 3.0) using the AMARES fitting algorithm; PCr was normalized to the sum of (PCr + Pi). The PCr time constant was calculated as previously described (36) using the following equation:

$$\tau = \Delta t / \ln [D / (D + Q)]$$

where t = time between contractions (4 s), Q = drop in PCr with each contraction, D = additional drop in PCr from rest until the steady state.

Muscle cross sectional area (CSA) was measured in the largest eight slices of the anterior and posterior leg compartments using Winvessel custom software. The average fat-free muscle CSA for the posterior compartment included both superficial and deep muscle was measured. Muscle force was quantified over the highest 500 ms. MVC is reported as the average of the highest two attempts before or during BOLD trials. Physical activity was quantified using the average daily total counts over 7 consecutive days. Subjects were instructed to wear the monitor all hours they were awake, except when bathing. If daily wear time was < 10 hours, the data were discarded.

Statistics

Reliability study—The reliability of BOLD was assessed using the coefficient of variation (CV) and the intraclass correlation (ICC) using a two-way random-effects ANOVA in OA-r. Repeated measures ANOVAs were used to evaluate differences between muscles and between visits; planned comparisons were used to compare main effects. Correlations between PA and peak BOLD responses were assessed with Pearson's r using the average peak BOLD response of trials without venous occlusion. Significance was set at $p < 0.05$. Data are reported as mean $\pm$ SD. Data were analyzed using IBM SPSS V22.

Age comparison study—For the age comparison study, independent t-tests were used to measure differences between age groups. Homogeneity of variance was assessed with Levene's test using Welch's correction when violated. Significance was set at $p < 0.05$. Data are reported as mean $\pm$ SD, unless noted. Data were analyzed using IBM SPSS V22.

Results

Reliability

The OA-r subjects (n=9) were 66 ± 5 yrs old with an average BMI of 29 ± 7 . OA-r had a large range of physical activity from sedentary to running 5 days a week (54×10^3 – 674×10^3 counts/day, mean = 257×10^3 counts/day). Individual and average BOLD responses for OA-r are shown in Figure 1. PF data were excluded (n=2) due to venous occlusion during one of the two visits. Repeated measures ANOVA for peak BOLD showed no interaction ($F(2,12)=0.728$, $p=0.503$) or main effect for visit number ($F(1,6)=0.092$, $p=0.772$). There was a main effect for muscle on peak BOLD response ($F(2,12)=7.017$, $p=0.010$); pairwise comparisons showed greater peak BOLD response for SOL compared to AC ($p=0.019$). Repeated measures for TTP BOLD showed no interaction ($F(2,12)=0.014$, $p=0.986$) or main effect for visit number ($F(1,6)=0.169$, $p=0.695$). There was a main effect for muscle on TTP ($F(2,12)=21.356$, $p<0.001$); SOL had longer TTP than AC ($p=0.001$) and longer TTP than MG ($p=0.038$). Repeated measures for half recovery time showed no interaction ($F(2,12)=1.085$, $p=0.369$) or main effect for visit number ($F(1,6)=2.098$, $p=0.198$). There was a main effect for muscle on half recovery time ($F(2,12)=58.135$, $p<0.001$); pairwise comparisons showed longer half recovery time for SOL compared to AC and MG ($p=0.014$).

All muscles had excellent ICC for peak BOLD (> 0.95). The CVs for peak BOLD response were 8.6%, 11.8% and 24.8% for SOL (n=7), AC (n=9) and MG (n=7), respectively. The ICCs for TTP were 0.830, 0.871 and 0.931 for SOL, AC and MG, respectively, with CVs ranging from 9.8–10.3%. The ICCs for half recovery time were 0.707, 0.923 and 0.826 with CVs of 16.2%, 18.0% and 32.0% for SOL, AC and MG, respectively. The peak force between trials was similar for DF and PF, approximately 94% of MVC (DF: Visit 1= 164 ± 43 N, Visit 2= 176 ± 38 N; PF: Visit 1= 205 ± 67 N, Visit 2= 196 ± 45 N; $p=0.18$). The correlations between peak BOLD responses and PA in OA-r (n=9) were significant for PF (SOL: $r=0.930$, $p<0.001$; MG: $r=0.744$, $p=0.021$) and DF (AC: $r=0.715$, $p=0.030$).

Age group comparison

Data from twelve YA and thirteen OA are reported. Venous occlusion excluded two YA and low PA excluded two OA (outliers). The physical characteristics of the final sample are shown in Table 1. BMI, systolic blood pressure, glucose and LDL were significantly higher in the older group. There were no statistical differences in PA between the groups. PA data is not reported from 3 subjects who failed to comply with the instructions to wear the monitor for complete days (all males, n=1 YA, n=2 OA). MVC was not significantly different between groups when expressed as an absolute value (N) or relative to muscle size (N/cm^2) (Table 2).

BOLD time courses and group responses are shown in Fig. 2. Peak BOLD response in the SOL was significantly greater in YA compared to OA, $t(16.4) = 2.618$, $p=0.017$, corrected for unequal variances (Fig.2). Peak BOLD response in the AC was also significantly greater for YA compared to OA, $t(16.3) = 3.139$, $p=0.006$. MG peak BOLD response was not different between groups, $t(23) = 0.746$, $p=0.465$. TTP BOLD and half recovery time were

not different between age group for any muscle region (Fig.2). Force during BOLD was ~94% of MVC and was not different between the groups for absolute or relative forces (Table 2).

The effect of age on peak BOLD response persists for SOL and AC even when more closely matching the groups for BMI (YA=25±4 vs. OA=27±5, $p=0.310$, removing (n=3) in each group) and when removing individuals with hypertension (n=3 OA). In this subgroup, SOL peak BOLD response was 4.7±1.5% for YA (n=9) vs. 3.0±0.6% for OA (n=7) and AC peak BOLD response was 2.6±1.1% for YA vs. 1.6±0.6% for OA, $p=0.026$. PA in this subgroup was also similar (YA=215±70 vs. 211±54, $p=0.908$). To further examine the influence of BMI on the peak BOLD response, the OA group was divided into 2 groups based on BMI; BMI-low (BMI<28, n=7, BMI=25±3, PA=192×10³ counts/day) and BMI-high (n=6, BMI=35±4, PA=216×10³ counts/day). SOL peak BOLD response was not statistically different between the groups (BMI-low group=3.2±0.7% vs. BMI-high group: 3.4±0.8%, $p=0.608$). The result was similar for the AC; Peak BOLD response was 1.5±0.5% and 1.7±0.6%, for BMI-low and -high, respectively ($p=0.411$). Thus a higher BMI in OA was not associated with lower peak BOLD responses.

MRS was only completed in 11 of the YA and 7 OA due to time constraints. Muscle oxidative capacity of the AC was not different between groups (YA: 31.2 ± 7.7 s; OA: 31.1 ± 6.1 s; $t(17) = 0.036$, $p = 0.972$). The average total drop in PCr was ~12% across both groups. There was no decrease in pH throughout the protocol; minimum pH was 7.002 ± 0.013. The average force was ~80% MVC throughout the protocol with no difference in average force between the groups (Table 2).

Discussion

The major finding of the study is reduced microvascular function in leg muscles of older adults compared to younger adults with similar PA and muscle oxidative capacity. In agreement, we previously showed that BOLD responses in the AC showed a negative correlation with age for adults between 18–58 years old (37). The current study extends these findings to adults over 60 and includes the posterior leg (SOL) as well as the AC. It is well documented that microvascular function can be influenced by BMI (32) and hypertension (11). To account for these factors in our study, we examined age-related BOLD differences in a BMI-matched subgroup without hypertension and the age effect remained significant. Furthermore, peak BOLD in OA was not influenced by BMI. Overall, these findings confirm the hypothesis that aging is associated with reduced microvascular function independent of PA. The findings are consistent with the reduced rapid onset vasodilation elicited by single brief contractions in older adults reported both in the brachial (4) and femoral (17) arteries measured by ultrasound. Our results are generally consistent with age related reductions in T2* MRI during reactive hyperemia (21, 34). However, these prior studies did not quantify or control for PA.

Reduced microvascular function with advancing age may be partially explained by changes in arteriole function. Studies in rodents show that both arteriole vasodilatory capacity as well as rate are reduced with age (3, 18). Age related reductions in rapid onset vasodilation in the

brachial artery of older adults were minimized after application of adrenergic receptor antagonists, suggesting a role for increased α -adrenergic vasoconstriction with aging (5). An age related reduction in NO sensitivity during single contractions has also been reported (6). Other vasodilators known to be involved in single contraction mediated hemodynamics, like potassium have not been examined during similar contraction protocols for age related reductions, but potassium channel contribution to myogenic tone has been shown to be reduced with age (20).

Capillary number and ultrastructure have also been reported to be reduced in older adults (8, 13, 14). Remarkably, reduced capillary density has been linked to reduced functional performance in aging and disease (26, 31). For example, older adults who had greater difficulty in daily task completion and walked slower had reduced capillary density (26). Interestingly, increased capillary density has recently been shown to correlate with improved insulin sensitivity in older adults after exercise training (30) suggesting a role of the microvasculature beyond physical function. Measures of microvascular function and rapid onset vasodilation may be even more predictive of physical functional outcomes compared to structural changes. These relationships, however, have not been evaluated.

The present study shows that microvascular function in older adults is influenced by PA (OA-r). It is generally accepted that PA improves vascular function (see review (43)). Exercise training is associated with an enhanced onset of blood flow responses (35) and low levels of activity are associated with a delayed onset of blood flow during exercise (27). Prior data showed three-fold greater BOLD responses in the AC for endurance trained young adults compared to sedentary adults (41). The present study extends the influence of PA on peak BOLD responses to older adults (OA-r) and to PF muscles. In a similar context, regular, chronic exercise training has recently been reported to blunt age related reductions in rapid onset vasodilation in the femoral artery (16). These findings collectively emphasize a major role for PA on hemodynamic responses.

Aging was not associated with reduced oxidative capacity for the AC consistent with other studies examining the AC oxidative capacity in older adults when PA levels are accounted for (39). Although we did not examine the oxidative capacity of the calf, results have shown that oxidative capacity in the calf is also not reduced with age (39). Our results show that reduced microvascular function is not directly linked to muscle oxidative capacity.

In young muscle, Sanchez et al., previously showed good reliability, based on ICC, for peak AC BOLD responses under similar conditions (TR/TE=1000/46ms, 10s MVC), but not for TTP (33). The reliability of peak and TTP BOLD response in older adults was excellent for AC and SOL. The reliability was lower for the MG, which may have contributed to the lack of BOLD differences between age groups. This may be explained by the ability to reliably recruit the MG. MG recruitment was reported to be lower during maximal effort compared to the SOL (7, 38). The ankle position, highly plantar flexed, may have also played a role as this is not the optimal angle for peak PF force. The time course for BOLD in the leg is muscle specific, with faster time to peak BOLD and half recovery time in the AC and MG compared to the SOL. The peak magnitude was also larger for SOL compared to the other leg muscles. These differences in hemodynamic response, especially between plantar

flexors, likely arise from the postural role for SOL compared to AC and MG (19). Capillary number and contacts are greater and capillary architecture is enhanced for SOL compared to MG (1). This finding of greater peak BOLD for SOL compared to other leg muscles was also observed with reactive hyperemia (34).

In this study, there were some challenges associated with BOLD MRI. In particular for the older adults, some subjects had a difficult time fully relaxing between each contraction or had involuntary twitches, which led to repeated scanning. Involuntary twitches, in particular in muscles below the knee, are increased with age (12). While twitches do not evoke substantial forces, they do create motion, which confounds the MRI post contractile response. The highly plantar flexed position of the foot may have played a significant role in involuntary action. A second major challenge is the potential for venous occlusion near the imaging region which may lead to venous filling. This may arise due to very low supine venous pressures (approaching 10 mmHg) in the deep calf veins (29). It has previously been reported that venous filling prior to reactive hyperemia greatly enhances the MRI BOLD response (9). To explore the influence of venous occlusion on the present protocol, we induced venous filling by occluding the popliteal vein by placing a 30mmHg cuff proximal to the knee during our single brief contraction protocol and the peak BOLD response increased from 3.5 to 8% (n=2).

In summary, aging was associated with reduced microvascular function, independent of physical activity levels. The results show robust reliability for SOL and AC contraction mediated BOLD imaging for assessing microvascular function. In addition, peak BOLD responses were positively related to PA suggesting that aerobic exercise interventions may improve microvascular function in older adults. Therefore, future studies are warranted to examine effective interventions to improve microvascular function in aging and in other populations with reduced microvascular function, such as diabetics with microvascular impairments. Given the reported relationship between compromised microvasculature and physical function, additional studies are encouraged that closely examine the physical functional consequences of decreased microvascular function.

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Fig. 1. BOLD test-retest reliability (OA-r). The average BOLD time course is shown following single brief maximal contraction (time 0) in three leg muscle regions during two separate visits (A). The peak BOLD response following 1-s MVC plantarflexion (SOL and MG) and dorsiflexion (AC) is shown for individuals (lines) and visit averages (bars) (B). The time to peak BOLD (TTP) for each muscle area is shown for individuals (lines) and visit averages (bars) (C). The half recovery time is shown in D. SOL=soleus, AC= anterior compartment, MG=medial gastrocnemius. *significantly > AC, †significantly > AC and MG, $p < 0.05$.

Fig. 2.

Age difference in microvascular BOLD. The BOLD time course is shown for each muscle region after 1s maximal voluntary contraction (mean $\pm$ SE) (A). The average peak BOLD, TTP (time to peak) BOLD and half recovery time are shown (mean $\pm$ SD) (B). OA=older adults, YA=young adults, SOL=soleus, AC= anterior compartment, MG=medial gastrocnemius, YA: n=12, OA: n=13, * $p < 0.05$, OA<YA.

Table 1

Descriptive Characteristics

	YA (n=12)	OA (n=13)
Age (yrs)	21 ± 1 *	64 ± 4
Male (n)	4	3
BMI (kg/m ²)	24 ± 4 *	30 ± 6
Systolic BP (mmHg)	120 ± 7 *	129 ± 9
Diastolic BP (mmHg)	78 ± 8	81 ± 6
Ankle-Brachial Index	1.12 ± 0.06	1.16 ± 0.07
PA (counts × 10 ³)	239 ± 73 (n=11)	203 ± 48 (n=11)
Glucose (mg/dL)	81 ± 7 *	90 ± 8
Insulin (μIU)	7.9 ± 5.8	8.0 ± 6.0
Triglycerides (mg/dL)	113 ± 75	102 ± 38
Total Cholesterol (mg/dL)	168 ± 39	189 ± 33
LDL (mg/dL)	86 ± 29 *	109 ± 24
HDL (mg/dL)	60 ± 22	60 ± 16

PA= physical activity

*
p < 0.05

Table 2**Muscle parameters**

	YA (n=12)	OA (n=13)
Anterior leg CSA (cm ²)	10.04 ± 1.77	9.99 ± 1.96
Posterior leg CSA (cm ²)	46.79 ± 9.09	43.61 ± 7.15
Dorsiflexion MVC (N)	220 ± 47	194 ± 54
Plantar flexion MVC (N)	299 ± 72	262 ± 78
Dorsiflexion MVC (N/cm ²)	20.67 ± 2.66	18.32 ± 4.45
Plantar flexion MVC (N/cm ²)	6.26 ± 1.73	5.82 ± 2.59
Dorsiflexion BOLD force (N)	208 ± 46	182 ± 51
Plantar flexion BOLD force (N)	284 ± 71	244 ± 76
Dorsiflexion ³¹ P force (N)	167 ± 35 (n=11)	149 ± 43 (n=7)

CSA = muscle cross sectional area, MVC = maximal voluntary contraction