Enhancing Strength and Postocclusive Calf Blood Flow in Older People With Training With Blood-Flow Restriction

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The response of calf-muscle strength, resting blood flow, and postocclusive blood flow (PObf) were investigated after 4 wk of low-load resistance training (LLRT) with and without blood-flow restriction in a matched-leg design. Ten untrained older individuals age 62–73 yr performed unilateral plantar-flexion LLRT at 25% 1-repetition maximum (1RM). One limb was trained with normal blood flow and the other had blood flow restricted using a pressure cuff above the knee. IRM, isometric maximal voluntary contraction, and isokinetic strength at 0.52 rad/s increased \((p < .05)\) more after LLRT with blood-flow restriction than with normal blood flow. Peak PObf increased \((p < .05)\) after LLRT with blood-flow restriction, compared with no change after LLRT with normal blood flow. These results suggest that 4 wk of LLRT with blood-flow restriction may be beneficial to older individuals to improve strength and blood-flow parameters.

**Keywords**: ischemia, vascular occlusion, strength training

Decreased strength (Skelton, Greig, Davies, & Young, 1994) and vascular function (Dinenno, Jones, Seals, & Tanaka, 1999) are two important changes associated with advancing age in humans. Lower levels of strength in older adults are associated with a decreased functional ability to perform daily tasks (Suzuki, Bean, & Fielding, 2001), an increased rate in falls (Skelton, Kennedy, & Rutherford, 2002), and physiological changes such as loss of bone-mineral density (Blain et al., 2001). Reductions in limb blood flow at rest (Dinenno, Seals, DeSouza, & Tanaka, 2001), during exercise (Proctor & Parker, 2006), and after reactive hyperemia (Sarabi, Millgard, & Lind, 1999) are also seen with advancing age and are associated with metabolic syndrome (Lind & Lithell, 1993) and impaired clearance of atherogenic lipids that contribute to dyslipidemia (Baron et al., 1990). Interventions that will limit or improve these changes and thus improve both functional ability and these risk factors for disease could have profound benefits for older adults.

One such intervention that has been recently shown to improve both strength and vascular function is low-load resistance training (LLRT) with blood-flow restriction (Patterson & Ferguson, 2010). We demonstrated in young women that using workloads as low as 25% 1-repetition maximum (1RM) with blood-flow restriction...
restriction was sufficient to improve dynamic, isokinetic, and isometric plantar-flexor strength by as much as 30% after 4 weeks of training. This is similar to the responses seen in other training studies using LLRT with blood-flow restriction in young (Burgomaster et al., 2003) and postmenopausal women (Takarada et al., 2000). We also demonstrated an increase in blood-flow capacity (postocclusion reactive hyperemia [PObf]; Patterson & Ferguson, 2010).

Although the effectiveness of this type of training is well established for increasing strength in healthy young populations, it has yet to be determined whether older adults can counteract the age-related declines in strength and vascular function using such an intervention. Therefore the aim of this study was to determine whether LLRT at 25% 1RM with blood-flow restriction can improve calf-muscle strength and limb blood flow in older adults. We hypothesized that the gains in both muscle strength and limb blood flow would be greater in LLRT with blood-flow restriction than in LLRT alone. The calf-muscle group was chosen because it is considered functionally important during posture and locomotor tasks. For example, Reeves, Spanjaard, Mohagheghi, Baltzopoulos, and Magnaris (2008) demonstrated that the ankle-joint plantar flexors of older adults operate close to their maximal joint-moment limits during stair descent and are therefore of critical importance during this type of activity. The calf-muscle group also permits noninvasive measurement of blood flow using venous occlusion plethysmography, which has to be performed on the distal limb to allow attachment of the mercury strain gauge and proximal occlusion cuff. We chose 25% 1RM based on our previous study (Patterson & Ferguson, 2010) that demonstrated changes in strength and blood flow after resistance training with occlusion in young women. Moreover, in the same study we showed similar changes in strength and blood flow between 25% and 50% 1RM. Other studies have used intensities as low as 20% 1RM, which also show beneficial effects (Abe et al. 2005).

**Methods**

**Participants**

Ten older adults (2 female, 8 male; age 67 ± 3 years, height 170.3 ± 6.7 cm, body mass 77.9 ± 7.8 kg) volunteered to participate in the investigation and were selected according to the exclusion criteria used to define “medically stable” older participants for exercise studies proposed by Greig et al. (1994). All participants were habitually physically active (assessed during prescreening by asking participants to detail the type, frequency, and volume of exercise performed per week), that is, performed regular physical activity such as walking, jogging, or gardening (two or three times per week, 30 min at a time), but none specifically performed resistance-exercise training. The participants were fully informed of the purposes, risks, and discomfort associated with the experiment before providing written, informed consent. This study conformed to current local guidelines and the Declaration of Helsinki and was approved by Loughborough University’s ethics committee.

**Overview of Experimental Procedures**

Participants initially performed a familiarization trial before the experimental protocol to become accustomed to all testing procedures and training devices. All
measurements and training procedures were conducted on the calf-muscle group. Participants were instructed in proper use of the resistance-exercise equipment and performed several plantar-flexion contractions using a light load (<25% 1RM) to mimic the type of actions they would perform during the training.

The experimental protocol consisted of baseline measurement of plantar-flexor strength, resting limb blood flow (Rbf), blood flow after 5 min of circulatory occlusion (PObf), blood pressure, and corrected calf girth (CCG); a 4-week plantar-flexor resistance-training program with and without blood-flow restriction; and posttraining strength and blood-flow measurements that were conducted in an identical manner to the baseline measurements. All pre- and posttesting and training procedures were performed on both limbs. Participants had their legs assigned to be trained with blood-flow restriction in a counterbalanced manner, with 5 participants training their dominant leg and 5 training their nondominant leg, based on dominance from 1RM strength. All pretraining tests were performed 3–5 days before the commencement of the resistance-training program (baseline), and posttraining measurements were performed 3–5 days after the final training session.

Muscle Strength

Plantar-flexion torque was recorded on both limbs with the subject lying prone and the foot firmly secured to the foot adapter of an isokinetic dynamometer (Cybex Norm, Cybex International, New York, NY). Straps were used about the hip to prevent forward displacement of the body during maximal plantar flexions. Participants were placed with the knee at full extension and the lateral malleolus aligned with the axis of rotation identified on the dynamometer. Before measurements of isometric maximal voluntary contraction (MVC), subjects performed five submaximal isometric plantar-flexion contractions as a warm-up. Three isometric MVCs were performed at a joint angle of 0° (the sole of the foot at 90° with respect to the tibial axis). The participants were asked to gradually but quickly attain MVC and hold for ~2–3 s. During each MVC constant verbal encouragement was provided by the investigator. Maximal isometric torque was taken as the highest value obtained during the three maximal contractions.

Isokinetic plantar-flexion torque was measured in the same position as during isometric MVC and was assessed by performing three, single, maximal repetitions. Before the maximal repetitions, five warm-up contractions were performed to accustom the participant to the required velocity. Torque production was assessed during the concentric phase of the movement only, at three different contraction velocities, 0.52, 1.05, and 2.09 rad/s (30, 60, and 120°/s). The highest torque value recorded during any of the three repetitions was taken as peak torque. The performance of each velocity was randomized, and 1 min rest was given between maximal efforts.

After a 15-min rest, dynamic plantar-flexor 1RM of each limb was assessed with a straight leg in a supine position on a leg-press machine. To bring the leg-press plate into position for straight-leg plantar-flexion exercise, the weight was initially pushed using knee extension with the help of an investigator. Once the participant was in a straight-leg position the plantar-flexion exercise could commence. After the participant had warmed up, the load was set at 80% of the predicted 1RM. After each successful lift the load was increased by ~5% until the subject failed to lift the load through the entire range of motion. A test was only considered valid when the participant used proper form and completed the entire lift in a controlled,
unassisted manner. Approximately 2–3 min of rest was allowed between attempts to ensure recovery. After it was judged that 1RM had been achieved, after a sufficient rest period each participant had the load increased one last time to ensure that they could not lift any more weight. On average each participant needed five attempts to reach 1RM. After the 4-week training period 1RM was reassessed. On this occasion, after a warm-up, the load was set close to the previous 1RM to ensure that a maximal effort was achieved before fatigue occurred.

**Limb Blood Flow**

Calf blood-flow measurements in both limbs were carried out in a supine position using venous occlusion strain-gauge plethysmography with mercury-in-rubber strain gauges (Hokanson, Bellvue, WA, USA). Mercury strain gauges were placed on the widest circumference of the calf. Inflation cuffs (CC17RB and SC10RB, Hokanson) were positioned 2–3 cm above the knee and around the ankle. Strain gauges were attached to a dual-channel plethysmograph (EC6, Hokanson), with blood-flow traces being sampled online at 100 Hz (Powerlab, AD Instruments, NSW, Australia). Venous drainage was facilitated by placing a 15-cm foam block under the ankle and a 7-cm foam block under the knee and ensuring that the limb was positioned in line with the heart. Rapid inflation of collection cuffs occurred by connecting the thigh cuff to a pneumatic air source (E20 Rapid cuff inflator and AG101 Cuff Inflator Air Source, Hokanson). Blood flow was calculated from the slope of the volume change over the first cardiac cycle, using Chart version 5 software (ADInstruments, NSW, Australia), and expressed in milliliters per minute per 100 ml of tissue. This method has previously been used to prevent contamination caused by venous congestion (Tschakovsky, Shoemaker, & Hughson, 1995). The coefficients of variation over repeated measurements of $R_{bf}$ and $PO_{bf}$ for the investigator were 10–11% and 7–10%, respectively. These correspond with values obtained from previous studies (Thijssen, Bleeker, Smits, & Hopman, 2005).

$R_{bf}$. After instrumentation participants rested for 20 min in a supine position. Resting blood pressure was obtained from the right arm of each participant (Omron M5-I, Omron Healthcare, Kruisweg, Netherlands) and repeated three times, with the average taken. Thirty seconds before the measurement of blood flow, arterial blood flow to the foot was occluded by inflating the ankle cuff to 200 mmHg. The measurement of blood flow was performed by inflating the thigh cuff to a venous occlusion pressure of 50 mmHg for 7 s, after which the cuff was deflated. This process was repeated three times, with approximately 30 s between measurements, and the average taken. The ankle cuff was deflated immediately after the final blood-flow measurement was obtained.

$PO_{bf}$. After $R_{bf}$, $PO_{bf}$ was measured while participants remained in the supine position by inflating the thigh cuff to 200 mmHg to induce arterial occlusion for 5 min. With 30 s left of arterial occlusion, an ankle cuff was inflated to 200 mmHg. After rapid deflation of the thigh cuff, blood-flow measurements were obtained within 15 s after arterial occlusion and every 15 s thereafter for 2 min. Peak $PO_{bf}$ was taken as the highest value obtained after occlusion. Total blood flow after 5 min occlusion was expressed in absolute terms as area under the time-flow curve calculated by the trapezoid method (Meeking, Browne, & Allard, 2000).
Anthropometry

Participants’ height was measured with a wall-mounted stadiometer (Holtain Ltd., Crymych, UK), and body mass, with a beam balance scale (Avery Ltd., Fairmount, MN, USA) while participants wore shorts and a T-shirt. Calf circumference was measured using a standard anthropometric tape, and medial calf skinfold was recorded by means of a vertical fold at the widest section of the muscle using Harpenden skinfold calipers (British Indicators Ltd., Wolverhampton, UK). The measures were taken on both limbs and repeated three times, to calculate the average value. From the values obtained, CCG was calculated by subtracting $\pi$ multiplied by the skinfold (in centimeters) from the total calf-circumference measurement, previously described by Martin, Spenst, Drinkwater, and Clarys (1990).

Training Protocol

The 4-week training program consisted of three sessions per week of supervised resistance training. Training consisted of plantar-flexion resistance exercise at 25% 1RM, as used in a previous study by Patterson and Ferguson (2010). After a warm-up involving two sets of 10 contractions of dynamic plantar flexion at <20% 1RM, participants performed single-leg plantar-flexion exercise using the same leg-press device employed for the dynamic 1RM strength test. For all training sets the restricted-blood-flow limb was trained first; participants completed three sets of exercise to the point of failure with 1-min rest intervals between sets. Vascular occlusion at 110 mmHg (Takarada et al., 2000) was maintained for the entire three sets (including rest periods), which resulted in a restriction period of ~5–8 min. After blood-flow-restriction exercise, 3 min rest was given before the control leg was exercised under the normal-blood-flow condition, in which the number of repetitions performed during the restricted condition was repeated for the control leg. This was done to ensure that the same amount of work was performed by the two limbs. Each limb’s 1RM was reassessed after 2 weeks of training, and loads were adjusted to maintain the required training intensity.

Statistical Analysis

Results are expressed as $M \pm SD$ for all variables. $R_{bf}$, peak $P_O_{bf}$, blood-flow area under the time-flow curve, 1RM, MVC, isokinetic strength, and CCG were examined using a two-way (Time × Limb) ANOVA with repeated-measures design. Systolic and diastolic blood pressure were examined using a paired-samples $t$ test. Statistical significance was accepted at $p < .05$. Effect size was measured using Pearson’s correlation coefficient ($r$; see Field, 2001), by converting the $F$ ratios using the following formula:

$$r = \sqrt{F(1,df_R)} / F(1,df_R) + df_R$$

Results

All the participants were able to successfully complete all training sessions with 100% compliance and free of injury or complications. No differences were found in any baseline variables between the restricted- and normal-blood-flow conditions.
CCG increased, main effect of time, $F(1, 9) = 11.68, p = .008, r = .75$, in the blood-flow-restricted group (34.1 ± 1.7–34.5 ± 1.6 cm) and the normal-blood-flow group (34.0 ± 1.8–34.4 ± 1.7 cm). However, there were no differences observed between groups, no main effect for limb, $F(1, 9) = 0.108, p > .05, r = .10$, or interaction of Limb $\times$ Time, $F(1, 9) = 0.015, p > .05, r = .04$.

Systolic blood pressure did not change, $t(9) = 0.035, p > .05, r = .11$, after resistance training (132 ± 22 and 131 ± 18 mmHg, pre- and posttraining). Diastolic blood pressure was also unchanged, $t(9) = 0.195, p > .05, r = .06$, after resistance training (79 ± 16 and 79 ± 15 mmHg, pre- and posttraining).

### Changes in Muscle Strength

Values of plantar-flexor 1RM, MVC, and isokinetic torque are shown in Table 1. At baseline, 1RM was similar between conditions. The increase in 1RM was greater when LLRT was performed with blood-flow restriction than with normal blood flow (14% vs. 4%, respectively), main effect for limb, $F(1, 9) = 5.63, p = .042, r = .62$; main effect of time, $F(1, 9) = 45.91, p = .000, r = .99$; interaction of Limb $\times$ Time, $F(1, 9) = 41.63, p = .000, r = .91$.

MVC increased more after LLRT with blood-flow restriction than with LLRT with normal blood flow (18% vs. 4%, respectively), no main effect for limb, $F(1, 9) = 0.06, p > .05, r = .25$; main effect of time, $F(1, 9) = 15.71, p = .003, r = .80$; interaction of Limb $\times$ Time, $F(1, 9) = 13.619, p = .005, r = .78$.

Isokinetic torque at 0.52 rad/s increased by 20% and not at all in restricted- and normal-blood-flow conditions, respectively (no main effect for limb), $F(1, 9) = 0.48, p > .05, r = .23$; main effect for time, $F(1, 9) = 5.61, p = .04, r = .62$; interaction of Limb $\times$ Time, $F(1, 9) = 15.15, p = .004, r = .79$.

Isokinetic torque at 1.05 rad/s increased, main effect of time, $F(1, 9) = 12.67, p = .006, r = .76$, by 17% and 4% for restricted- and normal-blood-flow conditions,

### Table 1  Changes in Plantar-Flexor Strength Parameters (1RM, MVC, and Isokinetic Torque) After 4 Weeks Resistance Training With and Without Blood-Flow Restriction, $M \pm SD$

<table>
<thead>
<tr>
<th>Strength parameter</th>
<th>Restricted Pretraining</th>
<th>Restricted Posttraining</th>
<th>Normal Pretraining</th>
<th>Normal Posttraining</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-repetition maximum (kg)</td>
<td>148 ± 25</td>
<td>168 ± 25*†</td>
<td>150 ± 25</td>
<td>155 ± 25</td>
</tr>
<tr>
<td>Maximal voluntary contraction (N/m)</td>
<td>85 ± 20</td>
<td>100 ± 26*</td>
<td>92 ± 26</td>
<td>95 ± 25</td>
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<tr>
<td>Isokinetic torque</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.52 rad/s (N/m)</td>
<td>83 ± 27</td>
<td>96 ± 21*</td>
<td>92 ± 25</td>
<td>92 ± 26</td>
</tr>
<tr>
<td>1.05 rad/s (N/m)</td>
<td>62 ± 21</td>
<td>69 ± 18</td>
<td>66 ± 19</td>
<td>69 ± 20</td>
</tr>
<tr>
<td>2.09 rad/s (N/m)</td>
<td>41 ± 16</td>
<td>45 ± 16</td>
<td>43 ± 15</td>
<td>44 ± 15</td>
</tr>
</tbody>
</table>

*Significant ($p < .05$) interaction between normal and restricted blood flow. †Significant ($p < .05$) main effect of group, normal to restricted blood flow.
respectively. However, there were no differences observed between groups, no main effect for limb, $F(1, 9) = 1.40, p > .05, r = .37$, and no interaction of Limb $\times$ Time, $F(1, 9) = 4.77, p > .05, r = .59$.

Isokinetic torque at 2.09 rad/s increased, main effect of time, $F(1, 9) = 8.55, p = .02, r = .70$, by 11% and 3%, for restricted- and normal-blood-flow conditions, respectively. However, there were no differences observed between groups (no main effect for limb), $F(1, 9) = 0.005, p > .05, r = .02$, and no interaction of Limb $\times$ Time, $F(1, 9) = 2.306, p > .05, r = .45$.

**Changes in Limb Blood Flow**

$R_{bf}$ was similar between conditions at baseline and remained unchanged after LLRT with $(2.1 \pm 0.5–2.4 \pm 0.5 \text{ ml} \cdot \text{min}^{-1} \cdot 100 \text{ ml}^{-1})$ and without $(2.2 \pm 0.6–2.5 \pm 0.8 \text{ ml} \cdot \text{min}^{-1} \cdot 100 \text{ ml}^{-1})$ blood-flow restriction, no main effect for limb, $F(1, 9) = 0.39, p > .05, r = .20$; or for time, $F(1, 9) = 3.943, p > .05, r = .55$; or interaction of Limb $\times$ Time, $F(1, 9) = 0.115, p > .05, r = .11$.

$P_{obf}$ was similar between conditions at baseline. It increased more after LLRT with blood-flow restriction than with normal blood flow (Figure 1), no main effect for limb, $F(1, 9) = 0.153, p > .05, r = .13$; main effect of time, $F(1, 9) = 29.666, p = .000, r = .88$; interaction of Limb $\times$ Time, $F(1, 9) = 15.804, p = .003, r = .80$.

Although $P_{obf}$ increased more with blood-flow restriction, the increase in area under the time-flow curve, main effect of time, $F(1, 9) = 29.782, p = .000 r = .87$, was the same between both the restricted- $(393 \pm 125–587 \pm 116 \text{ ml}/100 \text{ ml})$ and normal-blood-flow $(395 \pm 196–591 \pm 269 \text{ ml}/100 \text{ ml})$ conditions, no main effect for limb, $F(1, 9) = 0.002, p > .05, r = .01$, or interaction of Limb $\times$ Time, $F(1, 9) = 0.001, p > .05, r = .01$.

**Discussion**

The major finding of the current study was that in older individuals LLRT with blood-flow restriction resulted in greater improvements in maximal strength (1RM, MVC, MVC)}
isokinetic torque at 0.52 rad/s) and peak PO_{bf} than LLRT with normal blood flow.

Previous research in younger individuals has consistently shown increases in strength in the range of 10–22% after 4–16 weeks resistance training of various muscle groups (e.g., biceps and quadriceps) with blood-flow restriction (Burgomaster et al., 2003; Shinohara, Kouzaki, Yoshihisa, & Fukunaga, 1998; Takarada et al., 2000). The increases in dynamic plantar-flexion strength observed in the older participants in the current study are consistent with those observed in younger people (Patterson & Ferguson, 2010) and are of a magnitude similar to those observed during conventional high-load (>70% 1RM) resistance training in older individuals (e.g., Hakkinen, Kraemer, Newton, & Alen, 2001; Harridge, Kryger, & Stensgaard, 1999). Although we were not able to directly assess the degree of strength gains compared with conventional high-load resistance training, LLRT with blood-flow restriction may prove useful for individuals such as those recovering from injury or those suffering from complications that may not allow them to use heavy loads.

One reason is that it is plausible that the increases in strength during the initial stages of this type of training are greater than with conventional high-load resistance training, because the average increase in cross-sectional area of the muscle is as high as 0.57%/day during LLRT with blood-flow restriction (Abe et al., 2005), compared with the reported 0.03–0.26%/day gains seen during high-load resistance training (Wernbom, Augustsson, & Thomee, 2007). Second, we have demonstrated the feasibility of this type of training in older adults given the fact that our healthy participants completed the study with no complications or complaints, which may indicate that it is tolerable and safe. A previous report on safety issues with this type of training was issued by Nakajima et al. (2006), who surveyed over 105 Japanese facilities and their users (30,000 exercise sessions) who used LLRT with blood-flow restriction as a regular mode of exercise. They found that the most frequent safety issues were bruising at the location of the cuff (13.1%) and numbness (1.6%). There were reported cases of venous thrombosis (0.06%), but this was below the average number (0.2–0.26%) of cases seen in the Asian population (Klatsky, Armstrong, & Poggi, 2000). Further evidence for the safety of this type of training has been demonstrated by the work by Clark et al. (2010). They provided evidence that 4 weeks of LLRT with blood-flow restriction resulted in no adverse effects on vascular or nerve function and no markers of coagulation, fibrinolysis, or inflammation.

The changes in strength observed after 4 weeks training may be primarily a result of neural adaptations such as increased motor-unit recruitment, which typically occur during the early stages of resistance training (Folland & Williams, 2007). Addition of blood-flow restriction during low-intensity exercise results in additional recruitment of fast-twitch fibers (Krustup, Söderlund, Relu, Ferguson, & Bangsbo, 2009). In fact, the level of muscle activation during acute bouts of resistance exercise with blood-flow restriction is similar to that seen during resistance exercise with heavier loads (Takarada et al., 2000; Yasuda et al., 2009). However, after LLRT with blood-flow restriction in young people, both Moore et al. (2004) and Kubo et al. (2006) did not show an increase in activation level normally associated with resistance training with heavy loads. In those studies the activation levels were measured in younger individuals and were already at a high level, up to 98%, so further changes would seem unlikely. In men over the age of 50 it has been dem-
Resistance Training With Blood-Flow Restriction

Demonstrated that there is a significantly reduced activation level of the plantar flexors compared with younger counterparts (Kubo et al., 2007). Therefore it is possible that the greater increase in strength after LLRT with blood-flow restriction resulted from an increased level of activation. In addition to changes in neural activation, a change in pennation angle of the muscle may also explain the changes in strength. Muscles with large pennation angles allow more fibers to be arranged in parallel within a given cross-sectional area, thereby increasing a muscle’s force-generating potential (Manal, Roberts, & Buchanan, 2008). Kubo et al. (2006) demonstrated that LLRT with blood-flow restriction resulted in a change in the pennation angle of the muscle, which has been shown to occur in as little as 20 days (Seynnes, DeBoer, & Narici, 2007). There may also be an increase in the size of muscle; it has been previously shown that changes in muscle size after LLRT with blood-flow restriction occur as early as 2 weeks (Abe et al., 2005). In the current study there was a slight increase in CCG, but this was the same between conditions and it is acknowledged that CCG is not a direct measure of muscle size, which would be better measured by magnetic resonance imaging (MRI).

Decreased strength in older individuals is associated with impaired ability to independently perform everyday tasks (Skelton et al., 1994; Skelton et al., 2002). Resistance training with heavy loads has been shown to improve strength and counteract some of the associated functional impairments in older adults, such as walking and rising from a chair (Henwood, Riek, & Taaffee, 2008). It has recently been shown in people over 65 years old that LLRT with blood-flow restriction not only increases muscle strength but also improves specific functional tasks (Yokokawa, Hongo, Urayama, Nishimura, & Kai, 2008). Performance measures such as reaction time, timed up-and-go test, 10-m-walk time, maximum step distance, and balance tests all increased along with strength measures after 8 weeks of training. Therefore, the increase in strength of the plantar flexors seen in the current study may improve the participants’ functional ability, given the importance of this muscle group during functional tasks in older individuals (Reeves et al., 2008).

An important finding from the current study is that peak PObf was higher after resistance training with blood-flow restriction than with LLRT with normal blood flow. This is similar to our recent findings in young people (Patterson & Ferguson, 2010), with the changes in blood flow being of a similar magnitude. The exact mechanisms are unknown and are difficult to interpret using venous occlusion strain-gauge plethysmography but may include enhanced myogenic or metabolic response (Carlsson, Sollevi, & Wennmalm, 1987) or increased capillarity (Esbjornsson et al., 1993). An increase in muscle capillarity may be important in enhancing blood–tissue exchange properties, because in turn this increased capillary network may lead to an increased surface area for diffusion, a shortening of the average diffusion path length within the muscle, and possibly an increase in the length of time for diffusive exchange between blood and tissue (Prior, Yang, & Terjung, 2004). This improvement in the blood–tissue exchange may improve functional tasks requiring sustained activity. Moreover, the decrease in peripheral blood flow with aging (Dinenno et al., 1999; Ridout, Parker, & Proctor, 2005), including in older individuals who are overweight (Acree et al., 2007), is associated with metabolic syndrome, a major precursor to atherosclerotic disease in humans that includes hyperinsulinemia, dyslipidemia, and hypertension (Lind & Lithell 1993). Furthermore, reactive hyperemia has recently been indicated as being a
marker for cardiovascular disease (Addor et al., 2008). Therefore, strategies that can counteract this and increase limb blood flow, as we have demonstrated, may be important for reducing disease risk.

One limitation of the current study is the mixed-leg design. Cross-education is the contralateral effect of chronic motor activity in one limb (Enoka, 1988). Resistance training of a single limb has been shown to increase the strength of the nontrained limb, with a recent meta-analysis indicating that this cross-education accounts for an approximate 8% increase in strength (Carroll, Herbert, Munn, Lee, & Gandevia, 2006). Indeed, a cross-transfer in strength and hypertrophy has been reported after LLRT with blood-flow restriction (Madarame et al., 2008) and may be responsible for the increased strength in the control leg in the current study. This cross-education therefore may have resulted in the similar changes in torque at 1.05 and 2.09 rad/s in the two conditions. However, this may have also been a result of a lack of specificity in the testing procedure. The speeds employed in testing were much greater than the speeds used during training of the plantar flexors. This cross-education effect has also been shown to occur in the vascular system (DeSouza et al., 2000) and may be a result of the release of vasodilators into the circulation after exercise. However, not all evidence points to such an effect, with other studies not showing any change in the vascular bed of nontrained limbs (Gokce et al., 2002; Mourtzakis, Gonzalez-Alonso, Graham, & Saltin, 2004).

In conclusion, we have demonstrated that both strength and blood-flow parameters in older adults can be increased more after a 4-week training intervention using LLRT with blood-flow restriction than with LLRT alone. Future work should aim to establish the mechanisms behind these changes to aid in our understanding of reduced muscle mass and blood flow in older adults.

References


