Measurements of vascular function using strain-gauge plethysmography: technical considerations, standardization, and physiological findings

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Alomari, Mahmoud A., Angela Solomito, Rafael Reyes, Syed Muaz Khalil, Robert H. Wood, and Michael A. Welsch. Measurements of vascular function using strain-gauge plethysmography: technical considerations, standardization, and physiological findings. Am J Physiol Heart Circ Physiol 286: H99–H107, 2004. First published September 25, 2003; 10.1152/ajpheart.00529.2003.—The main purpose of the present study was to examine the relationships between measures of fitness [estimated peak oxygen consumption (\(V_\text{O}_2\text{peak}\)] and handgrip strength) and forearm vascular function in 55 young (22.6 ± 3.5 yr) adults. In addition, the present study considered methodological and technical aspects regarding the examination of the venous system using mercury in-Silastic strain-gauge plethysmography (MSGP). Forearm venous capacitance and outflow were examined using five different [7, 14, 21, 28, and 35 mmHg < diastolic blood pressure (DBP)] venous occlusion pressures and after a 5- and 10-min period of venous occlusion. A pressure of 7 mmHg < DBP and a period of 10 min venous occlusion produced the greatest (\(P < 0.05\)) venous capacitance and outflow, without altering arterial indexes. Reproducibility of forearm arterial and venous indexes were evaluated at rest and after 5 min of upper arm arterial occlusion at 240 mmHg on three different occasions within 10 days with the interclass correlation coefficient ranging from 0.70 and 0.94. Estimated \(V_\text{O}_2\text{peak}\) correlated with postocclusion arterial inflow (\(r = 0.54, P = 0.012\)) and resting venous outflow (\(r = 0.56, P = 0.016\)). Finally, handgrip strength was associated with venous capacitance (\(r = 0.57, P = 0.007\)) and outflow (\(r = 0.67, P = 0.001\)). These results indicate that the examination of forearm vascular function using MSGP is reproducible. Moreover, the data show the importance of careful consideration of the selection of venous occlusion pressure and period when implementing these measures in longitudinal trials. Finally, the associations between fitness and venous measures suggest a link between venous function and exercise performance.

THE RELATIONSHIP between exercise performance and arterial inflow is well documented (30). Surprisingly, the contribution of the venous system to overall cardiovascular function and skeletal muscle activities has received considerably less attention, despite compelling evidence demonstrating its importance beyond the typical role as a “passive volume reservoir” (3, 12, 40).

Additionally, few studies have examined the influence of physical fitness (cardiovascular and/or muscular) on indexes of venous function. The majority of these studies reported improvements in venous hemodynamics secondary to changes in blood volume after endurance training (5, 18, 21). More recently, Wecht et al. (43) attributed venous modifications, in part, to enhanced vasomotor tone, vessel compliance, and vessel responses to mechanical and neural stimulation. Therefore, the major aim of the present study was to examine relationships between measures of physical fitness and arterial and venous function. It was hypothesized that individuals with the highest levels of fitness would have greater arterial inflow and venous outflow patterns.

However, considering the lack of standardization and reliability of the protocols used to examine venous function, a secondary aim of the present study was to consider several methodological and technical aspects regarding the examination of the venous system.

METHODOLOGY

Study Design and Inclusion and Exclusion Criteria

This study consisted of two distinct phases. In phase I, two separate experiments were conducted to address methodological aspects (experiment I) concerning the examination of venous function and to determine the reliability (experiment 2) of vascular function using mercury in-Silastic strain-gauge plethysmography (MSGP). In phase II, two additional experiments were designed to examine the relationships of vascular function and cardiovascular fitness (experiment 3) and handgrip strength (experiment 4). Men and women between the ages of 18 and 35 yr were recruited to participate. Smokers and individuals with acute medical conditions (e.g., orthopedic injury), active infection, and/or on pharmacotherapy with known vascular effects (e.g., anti-inflammatory therapy, cardiovascular medications) were excluded. Before the experiments, subjects were instructed to fast and refrain from exercise for 12 h and alcohol for 48 h. After a comprehensive explanation of the study, its benefits, inherent risks, and expected commitments with regard to time, all participants signed an informed consent form approved by the Institutional Review Board of Louisiana State University.

Vascular Assessments

Instrumentations and measurements. Forearm arterial inflow, vascular resistance, venous capacitance, and outflow for all experiments were obtained using MSGP (model ECSR, D. E. Hokanson; Bellevue, WA). Upon arrival, blood pressure cuffs were positioned around the participant’s upper arm and wrist, and a mercury in-Silastic strain gauge (14) was placed around the forearm ~10 cm distal to the olecranon process while the subject was in the supine position. The forearm was extended and slightly supinated and elevated above the heart using a styrofoam block. Immediately before the blood flow measurements, hand circulation was occluded for 1 min by inflating the cuff at the wrist to 240 mmHg. Forearm blood inflow was estimated at rest and after 5 min of upper arm arterial occlusion.

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Examine the inspiratory in milliliters per kilogram per minute. Maximum handgrip strength apparently healthy young (age: 21.4)’s Christian Association (YMCA) cycle exercise test (2) in 21 men RBF, ml

Table 1. Subject characteristics

| Age, yr | 22.6±3.5 | 18–34 |
| Height, cm | 167.5±8.5 | 150–185 |
| Weight, kg | 69.1±15.2 | 43–114 |
| Arm length, cm | 25.5±2.2 | 20–30 |
| Arm circumference, cm | 25.17±3.0 | 21–35 |
| HR, beats/min | 59.0±10.0 | 45–93 |
| SBP, mmHg | 107.0±10.0 | 87–142 |
| DBP, mmHg | 62.0±8.0 | 46–86 |
| MAP, mmHg | 76.0±8.0 | 60–105 |

HR, heart rate; SBP, systolic blood pressure; DBP, diastolic blood pressure; MAP, mean arterial pressure.

Subsequently, forearm venous capacitance and outflow were obtained following specific venous occlusion pressures and periods as will be described below in each experiment. Arterial occlusion was achieved by inflating the cuff on the upper arm to 240 mmHg (1, 36). Throughout the testing procedures, heart rate and blood pressure were obtained at rest and during and immediately after occlusion.

Experiment 1: effect of varying occlusion pressure and time on vascular indexes. This experiment was conducted on 2 separate days in eight apparently healthy young men and women (age: 22.1±1.4 yr). Forearm blood inflow measures were obtained as described above in both days. On day 1, to examine the influence of varying upper arm venous occlusion pressures on venous capacitance and outflow, resting forearm venous indexes were evaluated after 4 min of upper arm venous occlusion pressure at 7, 14, 21, 28, and 35 mmHg below diastolic blood pressure. On day 2, to examine the influence of upper arm venous occlusion durations, venous capacitance indexes were taken every minute for a period of 10 min, and venous outflow was evaluated after 5 and 10 min of upper arm venous occlusion pressure using 50 mmHg.

Experiment 2: reliability of arterial and venous function measurements. Forearm blood inflow and venous capacitance and outflow were obtained in eight apparently healthy young men (age: 24.0±5.0 yr) on 3 different occasions within 10 days to determine between-day reliability of MSGP. Vascular indexes were evaluated at rest and after 5 min of upper arm arterial occlusion. Venous capacitance and outflow for the two conditions (rest and postocclusion) were evaluated after 6 min of upper arm venous occlusion at 7 mmHg below diastolic blood pressure.

Experiments 3 and 4: associations between physical fitness measures and arterial and venous function. These experiments were designed to examine relationships between forearm arterial and venous function indexes and measures of physical fitness [estimated peak oxygen consumption (VO2_peak) and handgrip strength]. Cardiorespiratory fitness (estimated VO2_peak) was determined using the Young Men’s Christian Association (YMCA) cycle exercise test (2) in 21 apparently healthy young (age: 21.4±1.4 yr) women and expressed in milliliters per kilogram per minute. Maximum handgrip strength was determined in 22 apparently healthy young (age: 24.5±5.0 yr) men as the average of three maximum consecutive contraction trials using a hand dynamometer (model 78010, Lafayette Instruments; Lafayette, IN) and expressed in pounds. Vascular indexes were evaluated at rest and after 5 min of upper arm arterial occlusion. Venous capacitance and outflow for the two conditions (rest and postocclusion) were evaluated after 6 min of upper arm venous occlusion at 7 mmHg below diastolic blood pressure.

Data Analysis

Arterial indexes. Resting forearm blood inflow was recorded at a paper speed of 5 mm/s, and values were derived from the slope drawn at the best-fit tangent using the first three pulses. Calculations were made as a function of 60 s divided by the horizontal distance (in mm) needed for the slope to rise vertically from the baseline to the top of the recording paper and multiplied by the full chart range. Peak arterial inflow after occlusion was recorded at a paper speed of 25 cm/s. Analyses were performed using a slope drawn at the best-fit tangent to the curves of the first two pulses of the flow curve after cuff release. The blood flows were then calculated from 60 s multiplied by the paper speed (25 cm/s) divided by the horizontal distance (in mm) needed for the volume slope to increase by 20 mm vertically. Mean arterial pressure (MAP) was calculated using the standard equation: MAP = diastolic blood pressure + [(systolic blood pressure – diastolic blood pressure)/3]. Forearm vascular resistance (FVR) was calculated by dividing MAP by forearm blood inflow (FVR = MAP/forearm blood inflow).

Venous indexes. Forearm venous capacitance was measured as the vertical distance (in mm) representing the increase in the forearm volume graph after the designated period (as described for each experiment) for venous filling. Analysis of forearm venous outflow was derived from a tangent line that represents the vertical drop in the volume graph from the excursion line and drawn at 0.5 and 2 s after the release of the venous occlusion pressure (6, 13).

Statistical Analysis

All statistical analyses were performed using SPSS statistical software for Windows (version 11.0; Chicago, IL). Group data are expressed as means ± SD, and α was set a priori at P < 0.05.

Experiment 1: effect of varying occlusion pressure and time on vascular indexes. To evaluate the difference in forearm inflow and venous capacitance and outflow after each venous occlusion pressure, repeated-measures ANOVA and the Bonferroni pairwise comparison were used. Dependent t-tests were used to compare vascular function measures at 5 and 10 min.

Experiment 2: reliability of arterial and venous function measurements. The interclass correlation coefficient (ICC) was used to determine the reliability of MSGP. Measures of the arterial and venous function indexes at rest and after occlusion were included.

Experiments 3 and 4: relationship between physical fitness measures and arterial and venous function indexes. Pearson’s product moment correlation was used to examine the relationship between physical fitness measures (estimated VO2_peak and handgrip strength) and arterial and venous function indexes as well as the relationship between arterial and venous function indexes. Additionally, with

Table 2. Resting vascular indexes after varying occlusion pressures

<table>
<thead>
<tr>
<th>Pressure, mmHg</th>
<th>7&lt;DBP</th>
<th>14&lt;DBP</th>
<th>21&lt;DBP</th>
<th>28&lt;DBP</th>
<th>35&lt;DBP</th>
</tr>
</thead>
<tbody>
<tr>
<td>RBF, ml·100 ml⁻¹min⁻¹</td>
<td>2.5±1</td>
<td>2.1±1</td>
<td>1.9±1</td>
<td>1.7±1</td>
<td>1.5±0.5</td>
</tr>
<tr>
<td>FVR, units</td>
<td>37.7±17‡</td>
<td>53±37</td>
<td>48±24</td>
<td>54±24</td>
<td>56.3±17</td>
</tr>
<tr>
<td>Venous capacitance, ml·100 ml⁻¹min⁻¹</td>
<td>3.7±0.7†‡</td>
<td>3.3±0.6‡</td>
<td>3.0±0.5†‡</td>
<td>2.4±0.7</td>
<td>2.2±0.5</td>
</tr>
<tr>
<td>Venous outflow, ml·100 ml⁻¹min⁻¹</td>
<td>32.7±4.5†‡</td>
<td>29.3±5.7‡</td>
<td>24.3±6†‡</td>
<td>21.5±5</td>
<td>17.3±4</td>
</tr>
</tbody>
</table>

Values are expressed as means ± SD. RBF, resting blood inflow; FVR, forearm vascular resistance. *P > 0.05 vs. 21 mmHg < DBP pressure; †P > 0.05 vs. 28 mmHg < DBP pressure; ‡P > 0.05 vs. 35 mmHg < DBP pressure.

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participants subdivided into above (high) and below (low) average fitness groups according to fitness classifications provided by the YMCA for estimated VO₂ peak and the Canadian Society of Exercise Physiology for handgrip strength (25), independent t-tests were used to compare fitness measures and vascular indexes.

RESULTS

Participant Characteristics

A total of 55 individuals (28 men and 27 women) volunteered to participate in these experiments. The participants’ characteristics are presented in Table 1.

Experiment 1: effect of varying venous occlusion pressure and time on vascular indexes. The results for experiment 1 are depicted in Table 2 as well as in Figs. 1, 2, and 3. There was no significant affect in altering the venous occlusion pressure and time on forearm resting or reactive hyperemic blood flow (Table 2). The data indicate a stepwise increase in measures of forearm venous capacitance (Fig. 1A) and outflow (Fig. 1B) with increasing venous occlusion pressures. In contrast, forearm inflow was not affected by the pressure maneuvers. Furthermore, forearm venous capacitance and outflow were consistently greater after 10 min compared with 5 min of venous occlusion (Fig. 2). Finally, venous capacitance showed a stepwise increase as the venous occlusion time increased (Fig. 3).

Experiment 2: reliability of MSGP to measure arterial and venous function indexes. Between-day reliability values using the ICCC are presented in Table 3. The ICCC values for the peak blood inflow and vascular resistance were 0.81 and 0.75, respectively. Additionally, resting and after upper arm arterial occlusion venous capacitance and outflow ICCC values ranged between 0.70 and 0.94.

Experiments 3 and 4: relationship between physical fitness measures and arterial and venous function indexes. The associations between measures of physical fitness and vascular function are presented in Table 4 and depicted in Figs. 4 and 5. Estimated VO₂ peak was significantly correlated with peak forearm blood inflow and vascular resistance and with venous outflow (Table 4). Further analysis revealed a significant difference in vascular function between those with high VO₂ peak estimates (46.4 ± 6.6 ml·kg⁻¹·min⁻¹) compared with the low fitness group (32.3 ± 3.4 ml·kg⁻¹·min⁻¹) (Table 5).

Handgrip strength was significantly correlated with venous capacitance and outflow at rest and after occlusion (Fig. 5, A and B). Moreover, as presented in Table 6, venous function indexes were different between the high (121.1 ± 10.6 lb) versus low (82.1 ± 14.9 lb) handgrip strength. No significant
associations were found between handgrip strength and forearm blood inflow at rest or after occlusion (see Table 4).

Finally, resting and peak forearm arterial inflow and vascular resistance correlated with resting and postocclusion venous capacitance and outflow (see Table 4).

DISCUSSION

This study was designed to examine the relationships between measures of physical fitness and arterial and venous function. In addition, methodological concerns and the reliability of arterial and venous function measures using MSGP were also addressed. Uniquely, the data indicate the magnitude of forearm venous outflow is positively associated with both cardiovascular (estimated VO_2_peak) and musculoskeletal (handgrip strength) fitness. Moreover, venous function measures are significantly influenced by the magnitude of the occlusion pressure and length of occlusion period without changes in arterial inflow. Finally, measures of arterial as well as venous function appear to be reasonably reproducible over a 10-day period.

Technical Aspects and Reliability of Vascular Measures

The postocclusion reactive hyperemia model has been used extensively to study vasodilatory responsiveness (16). Previous work from our laboratory has indicated adequate stability and reproducibility of this technique for the study of arterial reactivity under strictly controlled conditions using both ultrasonography (44) and plethysmography (22). Given recent information regarding the importance of the venous system on arterial function (3, 12, 40), the present study was designed to include information regarding venous function. Clearly, if the postocclusion model is extended to include information regarding venous function, it is essential that the reproducibility and limitations of the technique be established.

The data from experiment 1 indicate the importance of the selection of an appropriate venous occlusion pressure in the study of venous capacitance and outflow. The data reveal a stepwise decrease in venous capacitance and outflow as the magnitude of venous occlusion pressure from resting diastolic pressure was increased (see Fig. 1, A and B). The rationale for the examination of varying venous occlusion pressures is the lack of consensus regarding the selection of a standard pressure. Two different approaches in the selection of venous pressure appear to exist. The first is the use of a standard (usually 50 mmHg) venous occlusion pressure (6, 13), and the second is the use of a venous occlusion pressure based on the individual’s diastolic blood pressure (43). The present findings indicate that a venous occlusion pressure of 7 mmHg below diastolic blood pressure appears to yield greater venous capacitance and outflow compared with occlusion pressures further below the diastolic blood pressure. This is particularly important when considering longitudinal trials in which blood pressure is subject to change.

A second inconsistency in the literature is the duration of venous occlusion. Standard recommendations suggest venous occlusion periods of 2 min to examine venous capacitance and outflow (6, 13). The present data (see Fig. 2) clearly indicate that venous capacitance and outflow were greater after 10 min of venous occlusion at 50 mmHg compared with 5 min. The magnitude of the difference was particularly evident when we compared occlusion periods of 1–6 min, whereas the difference in the venous measures was less “drastic” with occlusion periods between 7 and 10 min (see Fig. 3). Thus, when implementing these measures in longitudinal trials, careful consideration should be given regarding the venous occlusion pressure and period. Interestingly, alterations in venous occlusion pressures and times did not have a significant effect on the arterial inflow measures.

**Table 3. Between-day ICC for forearm arterial and venous indexes**

<table>
<thead>
<tr>
<th>Conditions</th>
<th>RBF, ml·100 ml⁻¹·min⁻¹</th>
<th>FVR, units</th>
<th>Venous Capacitance, ml·100 ml⁻¹·min⁻¹</th>
<th>Venous Outflow, ml·100 ml⁻¹·min⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rest</td>
<td>0.29</td>
<td>0.30</td>
<td>0.78</td>
<td>0.94</td>
</tr>
<tr>
<td>Postocclusion</td>
<td>0.81</td>
<td>0.75</td>
<td>0.70</td>
<td>0.91</td>
</tr>
</tbody>
</table>

ICCC, interclass correlation coefficient.
Table 4. Pearson product moment correlation between arterial, venous, and physical fitness measures

<table>
<thead>
<tr>
<th>Variables</th>
<th>Resting Vascular Indexes</th>
<th>Postocclusion Vascular Indexes</th>
<th>Fitness Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Blood inflow</td>
<td>Vascular resistance</td>
<td>Venous capacitance</td>
</tr>
<tr>
<td>Resting vascular indexes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blood inflow, ml-100</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ml-1^{-1}min^{-1}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vascular resistance, units</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.001</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Venous capacitance, ml-100 ml-1^{-1}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ml-1^{-1}min^{-1}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Venous outflow, ml-100 ml-1^{-1}</td>
<td>0.013</td>
<td>0.002</td>
<td>0.0001</td>
</tr>
<tr>
<td>Postocclusion vascular indexes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blood inflow, ml-100</td>
<td>-0.007;</td>
<td>-0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>ml-1^{-1}min^{-1}</td>
<td>-0.2</td>
<td>0.27</td>
<td>0.018</td>
</tr>
<tr>
<td>Vascular resistance, units</td>
<td>-0.3;</td>
<td>0.06</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>-0.13;</td>
<td>0.55</td>
<td>0.04</td>
</tr>
<tr>
<td>Venous capacitance, ml-100 ml-1^{-1}</td>
<td>0.001</td>
<td>0.0001</td>
<td>0.0001</td>
</tr>
<tr>
<td>Venous outflow, ml-100 ml-1^{-1}</td>
<td>0.001</td>
<td>0.0001</td>
<td>0.0001</td>
</tr>
<tr>
<td>Fitness measures</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimated ( V_{O_2 \text{ peak}} )</td>
<td>0.04;</td>
<td>-0.3</td>
<td>-0.08</td>
</tr>
<tr>
<td>ml-kg^{-1}min^{-1}</td>
<td>0.876</td>
<td>0.2</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td>0.02;</td>
<td>-0.05</td>
<td>0.57</td>
</tr>
<tr>
<td>Handgrip strength, kg</td>
<td>0.93</td>
<td>0.8</td>
<td>0.007</td>
</tr>
</tbody>
</table>

\( V_{O_2 \text{ peak}} \) peak oxygen consumption.
Experiment 2 examined the reliability of measuring arterial as well as venous function using MSGP at rest and after occlusion over a 10-day period (see Table 3). The magnitude of the forearm blood flow values at rest and after occlusion are consistent with data from our laboratory (1) as well as others (36). The reliability measures used in the present study confirm adequate consistency between days for postocclusion flow measures (22, 29). In addition, the ICCC results indicate adequate reliability for venous capacitance and outflow at rest and after arterial occlusion. Resting blood inflow measures appear to vary considerably from visit to visit, despite the careful standardization of many external factors, such as meal timing, testing schedule, testing environment, subject placement, and subject clothing. This appears to be a consistent inconsistency in the literature and is difficult to rationalize (22, 29, 36). The values for these measures and the range from day to day are consistent with previously reported values from our (22) as well as other laboratories (29). However, it is important to consider the influence of the "wandering" baseline on the calculation of the blood flow difference between the peak blood flow response after the period of arterial occlusion and resting blood flow. The use of the absolute reactive hyperemic response would therefore appear to be more appropriate when using this model during longitudinal trials.

**Relationship Between Fitness and Vascular Function**

The ability to distribute and deliver adequate blood flow, oxygen, and nutrients to contracting skeletal muscle is recognized as a major contributor to exercise performance (30, 32). Data from the present study are consistent with this idea in that forearm vascular reactivity, defined as the peak blood flow response after arterial occlusion, was significantly related to estimated VO$_2$ peak (see Fig. 4). Although beyond the scope of this study, a physiological explanation for the associations between the peak blood inflow response and estimated VO$_2$ peak may involve either mechanical or chemical factors. For example, repetitive mechanical muscle contractions that initiate rhythmic modulations in blood inflow and vessel shear stress mediate upregulation of nitric oxide and/or prostacyclin enzyme pathways (34), inhibit norepinephrine release from adrenergic nerves (4), decrease sensitivity of the $\alpha_2$-adrenergic receptor to norepinephrine (8), and alter smooth muscle calcium kinetics (41). Alternatively, increased production of or sensitivity to local metabolites and vasoactive substances in distal tissue beds could play a role. In fact, a previous study (7) reports an increase in oxidative enzyme activity preceding the increase in vasoresponsiveness. Clearly, the speculations regarding the possible mechanism(s) for the observed associations need further refinement and experimental confirmation. Moreover, these speculations do not exclude the possibility of other explanations (e.g., increased muscle capillarizations, changes in neuroendocrine balance, myogenic factors, and/or cardiac function).

The main finding in the present study is the consistent associations between measures of venous function and cardiovascular and musculoskeletal fitness. These findings further confirm data from our laboratory suggesting that exercise tolerance in heart failure patients is related to venous function (45). The associations suggest the contribution of the venous system to overall cardiovascular performance and skeletal muscle activities is beyond the typical role as a passive volume reservoir.

![Fig. 4. A: relationship between estimated oxygen consumption (VO$_2$) and postarterial occlusion blood inflow. B: relationship between estimated VO$_2$ and resting venous outflow.](http://example.com/fig4)

![Fig. 5. A: relationship between handgrip strength and resting venous capacitance. B: relationship between handgrip strength and resting venous outflow.](http://example.com/fig5)
Arterial indexes

<table>
<thead>
<tr>
<th>Group</th>
<th>Blood inflow, ml·100 ml⁻¹·min⁻¹</th>
<th>Vascular resistance, units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>16.7±0.7</td>
<td>52.1±18.7</td>
</tr>
<tr>
<td>High</td>
<td>16.2±0.5</td>
<td>46.7±13.8</td>
</tr>
<tr>
<td>P values</td>
<td>0.46</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Venous indexes

<table>
<thead>
<tr>
<th>Group</th>
<th>Blood inflow, ml·100 ml⁻¹·min⁻¹</th>
<th>Vascular resistance, units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>3.8±0.8</td>
<td>40.7±7.9</td>
</tr>
<tr>
<td>High</td>
<td>4.0±0.7</td>
<td>49.5±9.7</td>
</tr>
<tr>
<td>P values</td>
<td>0.54</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Values are means ± SD.

Table 5. Differences between the cardiorespiratory groups in forearm arterial and venous indexes

Uniquely, the data of the present study reveal an association between venous outflow and estimated VO₂peak; and a greater venous outflow in the high cardiovascular fitness group. These results suggest that factors associated with venous function might play a role in exercise performance. Previous studies report that the venous system contributes to greater arterial dilation, with a subsequent increase in arterial blood inflow, muscle perfusion, and performance (3, 12, 40). Moreover, Barclay (3) demonstrated that muscle fatigue was delayed as a result of increased blood flow across the muscle bed independent of oxygen and/or nutrient delivery. Barclay (3) speculated the reduction in muscle fatigue was in part due to improved metabolic waste removal.

Another unique finding in the present study is the association between measures of venous function and handgrip strength, suggesting a link between muscular fitness and venous circulation. Further comparison reveals greater venous function measures in the high handgrip strength group, suggesting the importance of muscular fitness to venous function. Interestingly, individuals in the high-strength group reported long-term involvement in physical training. Because the venous system is controlled primarily by the sympathetic system (27), increased venous capacitance and outflow can be attributed to attenuated regional sympathetic venoconstriction associated with exercise training (28, 35, 37). This attenuation in sympathetic activities can be induced by alterations in metaboreceptors (37), mechanoreceptors stimulation (35), and/or a combination of both (28) and mediated by changes in regional neural reflex and/or adrenoceptor sensitivity (31). Recently, Wecht et al. (43) reported reduced venoconstriction in trained individuals, confirming these theories. Training may also result in an increased venous cross-sectional area by either recruiting already existing venules or the development of new venules (24, 38). Additionally, given the effect of exercise training on the arterial endothelium (7, 20), venular endothelium function might also be modified in the high-strength group as a result of either increased production of and/or venular relaxing factors. Combined, the above-mentioned factors may contribute to enhanced exercise performance secondary to augmentation of arterial inflow, improved metabolic waste removal from exercising muscles, and/or increased venous return (3, 9, 12, 40).

Given the numerous benefits of resistive exercise training in cardiovascular performance (10, 23, 47), as well as modification of the cardiovascular disease risk profile and overall health (17, 42, 46), the present findings suggest that resistance training might also benefit the venous system. This is particularly relevant considering venous abnormalities in aging (19, 26) and patients with heart failure (15, 33, 45) and venous diseases (11, 39). Therefore, recognizing the contribution of skeletal muscle in venous return and overall cardiovascular performance during exercise, factors associated with muscle strength modification might contribute to increased overall cardiovascular health subsequent to improved venous function, namely, venous outflow and capacitance. However, it is recognized that...
the present study is limited to a cross-sectional comparison, and future studies should be designed to directly examine whether resistance training and subsequent strength modifications can indeed alter venous function in both health and disease.

The association between arterial and venous measures suggests the presence of a communication link between the arterial and venous circulations. Interestingly, compelling evidence has emerged illustrating the importance of various aspects of the venous system beyond its typical role as a volume reservoir. In a recent study, Tschakovsky and Hughson (40) reported greater arterial inflow patterns with increased venous emptying after arm elevation. The authors linked these findings to the local venoarteriolar sympathetic axon reflex. The presence of nerve fiber collaterals from the sympathetic arteriolar plexus to adjacent venule reflex was initially described in 1991 by Rygaard et al. (31) and may serve as the anatomic substrate for the local venoarteriolar sympathetic axon reflex. Evidence of cross-communication between the arterial and venous circulations indicates that venular endothelium releases a relaxing factor(s) that contributes to the vasodilatation of adjacent arterioles (12). The optimal position of the venous circulation might provide a monitor of the tissue metabolic status and a potentially valuable feedback mechanism to control the arterial circulation. Therefore, the relationship between arterial and venous function indexes suggests that vasoreactivity and muscle perfusion might be influenced by venous hemodynamics, confirming the essential role of venous function in overall cardiovascular control, muscle contraction, and exercise performance (3, 12, 40).

In conclusion, these findings indicate the importance of recognizing the possible influence of venous occlusion times and pressures on venous capacitance and outflow. Additionally, the ICCC results indicate that MSGP is a reliable technique for measuring venous function on different days under controlled conditions and useful to differentiate between populations. Considering these technical aspects and establishing the reliability of MSGP are particularly relevant during cross-sectional as well as repeated-measures designs, especially in cases when blood pressure may be altered. Finally, forearm venous outflow is positively associated with measures of cardiovascular (estimated VO2 peak) and musculoskeletal (handgrip strength) fitness. The association between handgrip strength and venous system hemodynamics implies that muscular conditioning might be important for venous health, which warrants future studies examining the effect of muscular strength modifications on venous function.

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