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Title: Lower leg vascular conductance in triathletes

Authors:

Hayate Namatame[1], Hirokatsu Tayama[2], Seiji Maeda[3,4], Takeshi Otsuki[2*]

Affiliation (s):

[1] Graduate School of Comprehensive Human Sciences, University of Tsukuba, Ibaraki, Japan, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8577, Japan

[2] Faculty of Sport and Health Sciences, Ryutsu Keizai University, Ryugasaki, Ibaraki, Japan, 120 Ryugasaki, Ibaraki 301-8555, Japan

[3] Faculty of Health and Sport Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8577, Japan

[4] Faculty of Sport Sciences, Waseda University, 2-579-15 Mikajima, Saitama 359-1192, Japan

Mailing address: otsuki-takeshi@rku.ac.jp

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Abstract

Triathlon is an endurance sport that requires a high aerobic capacity. Previous studies demonstrated that lower-leg vascular conductance (VC) was associated with maximal oxygen uptake. However, it is unclear whether muscular VC is greater in triathletes versus untrained individuals. To test our hypothesis that VC in skeletal muscle is greater in triathletes relative to untrained peers and is associated with higher aerobic capacity in triathletes, this study investigated 10 male triathletes (21±1 years of age) and 8 untrained men (22±1 years). Triathletes exhibited greater maximal oxygen uptake than their untrained counterparts (61±6 vs. 39±6 mL/kg/min, $P < 0.01$), as well as lower heart rate (54±7 vs. 65±9 bpm, $P < 0.01$) and body fat (11±2 vs. 16±6 %, $P = 0.03$). There were no detectable intergroup differences in systolic (115±8 vs. 117±9 mmHg, $P = 0.74$), mean (83±6 vs. 86±8 mmHg, $P = 0.30$), or diastolic (62±6 vs. 65±7 mmHg, $P = 0.49$) blood pressure. Lower-leg blood flow (4.2±1.3 vs. 2.5±0.9 mL/dL/min, $P = 0.01$) and VC (0.05±0.01 vs. 0.03±0.01 mL/dL/min/mmHg, $P = 0.02$) based on venous occlusion plethysmography were greater in triathletes versus untrained men. Maximal oxygen uptake was correlated with lower-leg blood flow ($r = 0.70$, $P < 0.01$) and VC ($r = 0.69$, $P < 0.01$). These results demonstrate that lower-leg VC is higher in triathletes than in untrained individuals, and it may be associated with higher aerobic capacity in triathletes relative to untrained counterparts.

Keywords: blood flow; maximal oxygen uptake; vascular resistance

トライアスロン選手の下腿血管コンダクタンス

生田目颯[1]，田山寛豪[2]，前田清司[3,4]，大槻毅[2]

[1] 筑波大学大学院人間総合科学学術院，[2] 流通経済大学 スポーツ健康科学部

[3] 筑波大学体育系，[4] 早稲田大学スポーツ科学部

トライアスロンは高い有酸素性能力を必要とする持久系スポーツである．先行研究では，下腿の血管コンダクタンス（vascular conductance, VC）は最大酸素摂取量と関連することが示されている．しかしながら，トライアスロン選手において骨格筋のVCが非鍛錬者に比べて大きいか否かは不明である．本研究では，骨格筋のVCは非鍛錬者に比べてトライアスロン選手で大きく，トライアスロン選手の高い有酸素性能力と関連しているという仮説を検証するために，男性トライアスロン選手10人（21±1歳）および非鍛錬者8人（22±1歳）を対象に測定を行った．トライアスロン選手は，非鍛錬者よりも最大酸素摂取量（61±6 vs 39±6 mL/kg/min, $P < 0.01$）は多く，心拍数（54±7 vs 65±9 bpm, $P < 0.01$）および体脂肪率（11±2 vs 16±6 %, $P = 0.03$）は低かった．収縮期血圧（115±8 vs 117±9 mmHg, $P = 0.74$），平均血圧（83±6 vs 86±8 mmHg, $P = 0.30$），拡張期血圧（62±6 vs 65±7 mmHg, $P = 0.49$）に両者間の有意差は認められなかった．静脈閉塞プレチスモグラフィで測定した下腿の血流量（4.2±1.3 vs 2.5±0.9 mL/dL/min, $P = 0.01$）およびVC（0.05±0.01 vs 0.03±0.01 mL/dL/min/mmHg, $P = 0.02$）は，トライアスロン選手で非鍛錬者より高値を示した．最大酸素摂取量と下肢の血流量（$r = 0.70, P < 0.01$）および VC（$r = 0.69, P < 0.01$）との間に相関関係が認められた．これらの結果は，下腿VCは非鍛錬者よりもトライアスロン選手で大きいことを示唆する．トライアスロン選手の下腿VCは非鍛錬者に比べて有酸素性能力が高いことに関連するかもしれない．

Introduction

Triathlon, which consists of swimming, biking, and running, is an endurance sport that requires high aerobic capacity[1)]. Since maximal oxygen uptake, the gold standard for evaluating aerobic capacity, is strongly correlated with maximal cardiac output, blood circulation plays a crucial role in aerobic capacity[2)]. The main components of the circulatory system are the heart and blood vessels. Whereas many previous studies have investigated cardiac function in triathletes[3)], vascular function in this population has not been fully elucidated.

Vascular conductance (VC) in skeletal muscle may contribute to aerobic capacity since the peak VC in the lower leg after calf exercise is correlated with maximal oxygen uptake [4-6)]. However, it is unclear whether muscular VC is greater in triathletes than in untrained individuals. First, triathlon requires both aerobic capacity and muscular strength. Previous studies have demonstrated that triathletes have excellent aerobic capacity[7)]. On the other hand, Etxebarria *et al.*[8)] reported that cycling of triathlon requires high power output; power output per body weight during cycling of elite-level triathlon race was similar to those of hill climbers. Therefore, triathletes are supposed to be adapted to both endurance and strength training. Capillary density increases with endurance training but not with strength training[9)]. Second, previous studies reported that while systemic vascular resistance (VR, the inverse of VC) was comparable in triathletes and their sedentary counterparts[10)], pulmonary VR was higher in triathletes[11)]. Thus it has been unclear if muscular VC is greater in triathletes relative to untrained individuals. To test our hypothesis that VC in skeletal muscle is greater in triathletes versus untrained individuals and is associated with higher aerobic capacity in triathletes, we investigated lower-leg VC and maximal oxygen uptake in male triathletes and their untrained counterparts.

Methods

Participants

Study participants comprised 10 male triathletes (triathlon career, 7±5 years) in university triathlon clubs and 8 healthy male university students who did not regularly exercise. Inclusion criteria of triathletes were intercollegiate triathletes belonging to triathlon teams with at least 1 year of triathlon career and with training frequency of 5 or more days per week. Five of them had satisfied the entry standards for the Japan Triathlon Championships (*i.e.*, listed in the top 40 of NTT Japan Cup Ranking or met the qualifying standard [04:38.30 for swimming of 400 m and 09:40.92 for running of 3 km]). Inclusion criteria of untrained men were university students who had sedentary lifestyles (no regular physical activity except for sport classes in a university or high school) for at least 3 years. All were non-smokers, took no medications, and had no chronic diseases. The participants refrained from alcohol consumption and high-intensity exercise on the day before testing, and avoided caffeine consumption on the day of the study. Additionally, they did not eat or drink anything except for water for 2 hours prior to the measurements. After at least 10-minute of rest in the supine position in the air-conditioned laboratory, femoral-ankle pulse wave velocity (PWV) and brachial and post-tibial arterial blood pressure were measured simultaneously. Next, lower-leg blood flow (BF) was measured in the supine position. The resting data of vascular measurements were considered as acceptable if resting of the participants were kept during the rest and measurement periods. Finally, a maximal exercise test was performed to measure maximal oxygen uptake.

This study conformed to the principles of the Declaration of Helsinki and was approved by the Ethics Committee of the Ryutsu Keizai University (approval number 25). All participants provided written informed consent prior to study participation.

Lower-leg BF and VC measurements

Lower-leg BF and VC were measured using venous occlusion plethysmography with a mercury-filled strain gauge (EC6; Hokanson, Bellevue, WA, USA)[12]. A strain gauge was attached to the widest part of the lower leg. Briefly, an ankle cuff was inflated to 50 mmHg above post-tibial arterial systolic blood pressure (SBP) at 1 min before BF measurements began. A femoral cuff was rapidly inflated to 40–50 mmHg for 7 s during a 15-s cycle (E20; Hokanson). BF was calculated as the percent change in lower-leg volume during the occlusion phase. VC was calculated as BF divided by post-tibial arterial mean blood pressure (MBP).

Maximal oxygen uptake and body fat measurements

After the participants underwent a voluntary warm-up (*e.g.*, muscular stretching), a maximal exercise test (4 min at 100 W, with a 30-W increase every 2 min) was conducted using a cycle ergometer (75XL; Konami Sports, Tokyo, Japan). Breath-by-breath oxygen uptake and carbon dioxide production (AE300S; Minato Medical Science, Osaka, Japan), heart rate (HR) calculated using 3-lead electrocardiography (LRR-03; GMS, Tokyo, Japan), and rating of perceived exertion (RPE, Borg's 6–20 scale) were measured during the exercise test. We considered a participant as having achieved maximal exertion when at least 2 of the following 4 criteria were met; 1) a plateau in oxygen uptake with increasing exercise intensity (<100 mL/min); 2) achievement of age-predicted maximal HR (±10 bpm); 3) a respiratory exchange ratio of at least 1.15; and 4) an RPE of at least 18 units[13,14].

To demonstrate that the participants in this study were well-trained triathletes, body fat was measured using a body impedance–based body composition analyzer (InBody 430; InBody, Seoul, South Korea).

Femoral-ankle PWV and blood pressure measurements

Femoral-ankle PWV, an index of leg arterial stiffness, was measured using applanation tonometry and air plethysmography. Femoral and post-tibial artery pulse waves were obtained using a pulse wave analyzer (BP-203RPE II; Fukuda Colin, Tokyo, Japan). Pulse wave transit time, the delay between the proximal and distal waveforms, was automatically determined by the device. The distance between the femoral and post-tibial recording sites was assessed over the surface of the body, and PWV was calculated as the distance divided by the transit time. Simultaneously, SBP, MBP, and diastolic blood pressures (DBP) were measured in the brachial and post-tibial arteries using oscillometry (BP-203RPE II; Fukuda Colin). HR was calculated using electrocardiography (BP-203RPE II; Fukuda Colin).

Statistical Analysis

Statistical analyses were performed using Statistical Package for Social Sciences (SPSS) for Windows 27 (IBM, Armonk, NY, USA). Values are presented as means ± SDs. Normal distribution of variables was evaluated with the Shapiro-Wilk test. The unpaired *t* test was used for comparisons between the 2 groups. Relationships between 2 variables were investigated using Pearson’s correlation coefficient. *P*-values < 0.05 were considered statistically significant.

Results

All variables were distributed normally. There were no significant intergroup differences in age, height, or body weight (Table 1). Compared to their untrained counterparts, triathletes demonstrated significantly lower body fat (Table 1) and HR (Table 2) and significantly greater lower-leg BF based on venous occlusion plethysmography (Figure 1) and maximal oxygen uptake (Figure 2). There were no detectable intergroup differences in blood pressure and femoral-ankle PWV (Table 2). Compared to untrained individuals, triathletes had significantly greater lower-leg VC (Figure 3).

Maximal oxygen uptake was correlated with body fat, HR, and lower-leg BF and VC based on venous occlusion plethysmography (Table 3).

Discussion

This study measured lower-leg VC based on venous occlusion plethysmography, maximal oxygen uptake, and other indices in male triathletes and age-matched untrained men. Compared to their untrained counterparts, triathletes demonstrated significantly lower body fat and HR, and significantly greater lower-leg VC and maximal oxygen uptake. Additionally, lower-leg VC was correlated with maximal oxygen uptake. The results demonstrate that lower-leg VC is greater in triathletes than in untrained individuals, and it may be associated with higher aerobic capacity in triathletes relative to untrained peers.

Lower-leg VC based on venous occlusion plethysmography was higher in triathletes versus untrained men in this study. This result is inconsistent with previous studies investigating systemic and pulmonary VR (the inverse of VC) in triathletes. Lakin *et al.*10) reported that there was no difference in systemic VR between triathletes and sedentary individuals. However, it is possible that there are differences between systemic and peripheral vascular adaptations to exercise, since systemic VR transiently decreased after swimming while forearm VR increased12). Domenech-Ximenos *et al.*11) demonstrated that pulmonary VR was higher in triathletes compared to sedentary peers. Again, the discrepancy between the study of Domenech-Ximenos *et al.*11) and our own is not surprising because there are significant differences between the systemic and pulmonary circulations (*e.g.*, blood pressure and roles in oxygen delivery). The inconsistencies between this and previous studies10,11) do not cast doubt on the conclusions of this study.

It is apparent that the skeletal muscles of the lower leg play an important role in the bike and run portions of triathlon. In particular, the soleus is the largest muscle of the triceps surae15) and contributes to upward and forward center-of-mass acceleration during running more than other skeletal muscles16). Regarding biking, electromyography showed that the activity of the soleus increased with increasing workload17). We measured VC in the lower leg because previous studies showed that the peak value of lower-leg VC after calf exercise was correlated with maximal oxygen uptake during running4,6) and pedaling exercise5). This was a cross-sectional study, but it is possible that the correlation between lower-leg VC based on venous occlusion plethysmography and maximal oxygen uptake implies that high VC in triathletes contributes to their significant aerobic capacity.

In swimmers18), cyclists18,19), runners4,6), and endurance athletes (sport event was not described)5), there were no significant differences in resting lower-leg VC or VR between athletes and sedentary individuals. On the other hand, Hepple *et al.*4) demonstrated that lower-leg VC at rest was greater in body builders versus sedentary individuals, runners, and power athletes, and they speculated that high-repetition and high-intensity resistance exercise training in body builders may be implicated in vascular adaptations. High-repetition and intensive resistance exercise is also required in the triathlon during swimming and also during biking, especially on ascending slopes, just after sharp corners, and while increasing speed8). However, not only triathletes but also swimmers swim, and cyclists also do biking. The point makes triathlon unique is conjunction of these exercises and running. Eccentric muscle contractions of lower leg are involved in running whereas concentric contractions are dominant in cycling and swimming20). Kano *et al.*21) reported that eccentric gastrocnemius muscle contractions increased capillary luminal area in the muscles. Combination of high-repetition and intensive resistance exercise during swimming and biking and eccentric muscle contractions during running may be associated with greater VC in triathletes.

Resting HR was lower in triathletes versus sedentary men. Generally, endurance-trained athletes with lower resting HR have eccentrically remodeled left ventricle and higher stroke volume22). Additionally, previous studies demonstrated eccentric remodeling of left ventricle in triathletes11,23,24). We can speculate that triathletes in this study also had eccentrically remodeled heart and higher stroke volume. Greater stroke volume increases maximal oxygen uptake in endurance-trained athletes2). It is not surprising that resting HR was correlated with maximal oxygen uptake in this study.

According to the two-element Windkessel model, VC and arterial stiffness are the major vessel factors affecting hemodynamics. VC is mainly determined by internal diameter of peripheral arteries, and higher VC indicates superior blood transport capability. Arterial stiffness is an inverse of distensibility of arterial wall and associated with ability to buffer fluctuations of blood pressure and flow. Therefore, we measured not only lower-leg VC but also femoral-ankle PWV, an index of leg arterial stiffness. However, there was no detectable difference in femoral-ankle PWV between triathletes and sedentary counterparts. Previous studies on femoral arterial stiffness in runners and swimmers25) and cyclists26) reported conflicting results. The result of this study is consistent with the study of Nualnim *et al.*25) that there were no significant differences in femoral arterial stiffness among runners, swimmers, and sedentary peers. Leg artery is a muscular artery with less compliant walls; contribution to blood flow and pressure is greater in VC versus arterial stiffness in peripheral muscular arteries. Adaptation of leg arterial stiffness may be non-essential for triathletes.

This study demonstrated that triathletes have greater lower-leg VC based on venous occlusion plethysmography and that the higher VC is associated with higher aerobic capacity. The lower-leg VC could be used as an index of conditioning of triathletes and to discover a talented triathlete. A decrease in VC with aging increases blood pressure. Again, aerobic capacity is a predictor of cardiovascular events27). Investigating vascular adaptations to triathlon could potentially demonstrate the beneficial effects of triathlon as a lifelong sport.

This study has several limitations. First, this was a cross-sectional study with a small sample size. Second, we did not investigate the mechanisms underlying the greater VC in triathletes. Third, we demonstrated that VC is correlated with maximal oxygen uptake but did not conduct multivariate analysis due to small sample size. It is difficult to ascertain whether the correlation between VC and maximal oxygen uptake suggests a causal relationship. Further studies are warranted to establish the effects of triathlon on vascular function.

Conclusions

Triathletes have higher VC of the lower leg compared to untrained individuals, and it may be associated with higher aerobic capacity relative to untrained counterparts.

Conflict of interests

None.

Author contributions

HN and TO conceived, designed, and performed the experiments; HN analyzed data, prepared figures, and drafted the manuscript; HT, SM, and TO revised the manuscript; and all authors approved the final version of the manuscript.

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Table 1. Characteristics of participants.

	Triathletes	Untrained	*P* value
n	10	8	
Age, years	20.7 ± 1.3	21.5 ± 1.1	0.17
Height, cm	169 ± 6	171 ± 5	0.49
Weight, kg	63.3 ± 7.6	64.2 ± 8.9	0.82
Body fat, %	11.4 ± 2.1	16.2 ± 6.0	0.03

Values are means ± SDs.

Table 2. Blood pressure, heart rate, and arterial stiffness.

		Triathletes	Untrained	*P* value
Brachial	SBP, mmHg	115 ± 8	117 ± 9	0.74
	MBP, mmHg	83 ± 6	86 ± 8	0.30
	DBP, mmHg	62 ± 6	65 ± 7	0.49
Post-tibial	SBP, mmHg	133 ± 10	131 ± 12	0.74
	MBP, mmHg	87 ± 6	86 ± 9	0.77
	DBP, mmHg	66 ± 6	67 ± 8	0.91
Heart rate, bpm		54 ± 7	65 ± 9	0.01
Femoral-ankle PWV, m/s		7.9 ± 0.9	7.6 ± 0.7	0.47

Values are means ± SDs. SBP, systolic blood pressure; MBP, mean blood pressure; DBP, diastolic blood pressure; and PWV, pulse wave velocity.

Table 3. Correlation with maximal oxygen uptake.

	Maximal oxygen uptake	
	r	*P* value
Body fat	- 0.53	0.02
Heart rate	- 0.56	0.01
Lower-leg BF	0.70	< 0.01
Lower-leg VC	0.69	< 0.01

BF, blood flow and VC, vascular conductance.

Figure Legends

Figure 1. Lower-leg blood flow (BF) in male triathletes and untrained men.
Values are means ± SDs.

Figure 2. Aerobic capacity in male triathletes and untrained men.
Values are means ± SDs.

Figure 3. Lower-leg vascular conductance (VC) in male triathletes and untrained men.
Values are means ± SDs.

Figure 1
(Namatame et al.)

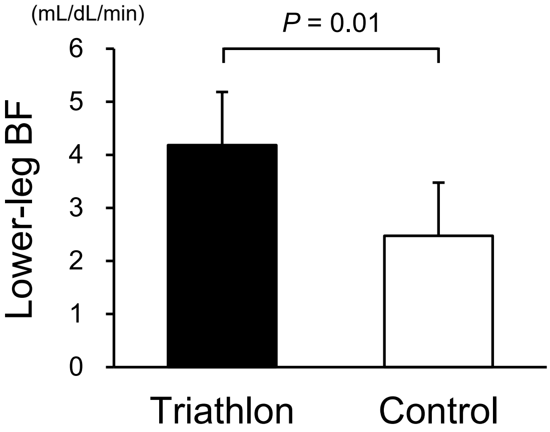

Figure 2
(Namatame et al.)

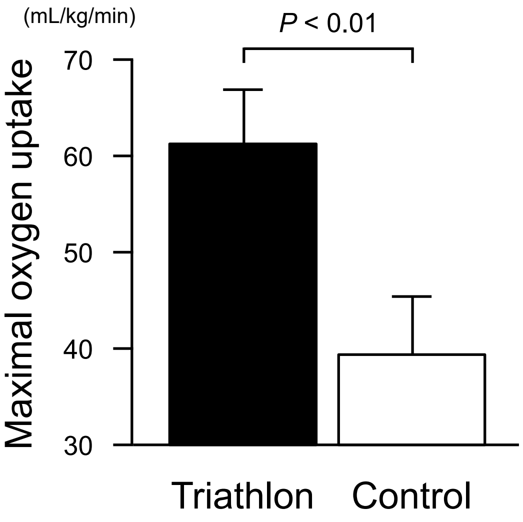

Figure 3
(Namatame et al.)