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ORIGINAL ARTICLE

Age and cardiorespiratory fitness are associated with arterial stiffening and left ventricular remodelling

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Arterial stiffening, hypertension and left ventricular (LV) remodelling are associated with increased risk of cardiovascular disease. Cardiorespiratory fitness is associated with cardiovascular function and reduced risk of cardiovascular disease. This cross-sectional study was carried out to determine the relationships between cardiorespiratory fitness, arterial stiffness, blood pressure (BP) and LV remodelling in women. On the basis of peak oxygen uptake, a total of 159 premenopausal (young) and postmenopausal (older) women were categorized into either low (unfit) or high (fit) cardiorespiratory fitness groups. The arterial stiffness and LV remodelling were measured by brachial-ankle pulse wave velocity (baPWV) and carotid augmentation index (AI) and LV relative wall thickness (RWT). Two-way analysis of variance indicated a significant interaction between age and cardiorespiratory fitness in baPWV, carotid AI, BP and RWT. In the older group, arterial stiffness (baPWV; 1401 ± 231 vs 1250 ± 125 cm s^{-1}, $P<0.01$, AI; 32.9 ± 9.9 vs 24.8 ± 10.1%, $P<0.01$), systolic blood pressure (SBP) (130 ± 22 vs 117 ± 15 mm Hg, $P<0.01$) and RWT (0.47 ± 0.08 vs 0.42 ± 0.04, $P<0.05$) in fit women were lower than in unfit women. In older women, RWT was significantly related to baPWV ($r=0.46$, $P<0.01$), carotid AI ($r=0.29$, $P<0.05$), SBP ($r=0.57$, $P<0.01$) $\dot{V}_{2peak}$ ($r=-0.32$, $P<0.05$). In young women, they were not significant correlations, except for a weak correlation between RWT and SBP ($r=0.21$, $P<0.05$). These results suggest that higher cardiorespiratory fitness is associated with lower arterial stiffness, BP and RWT in older women.

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Keywords: ageing; arterial stiffness; fitness; left ventricle; remodelling

Introduction

The cardiovascular system is affected by ageing. Arterial stiffness increases progressively with advancing age even in healthy men and women.[1] This arterial stiffening is associated with future hypertension[2] and death from cardiovascular disease.[3] Moreover, left ventricular (LV) relative wall thickness (RWT) (ratio of wall thickness to chamber radius) also increases with age (LV remodelling).[4] LV remodelling is often associated with LV systolic and diastolic dysfunctions[5] and all-cause mortality.[6] The risk of cardiovascular disease in women increases sharply after menopause,[7] which is associated in part with arterial stiffening, hypertension and LV remodelling.[8] Accordingly, the prevention and treatment of age-related arterial stiffening, hypertension and LV remodelling in women are of great clinical importance.

Cardiorespiratory fitness is strongly associated with risk of cardiovascular disease[9] and high blood pressure (BP).[10] Previous studies have indicated that age-related increases in arterial stiffness were attenuated in higher-fit adults.[11,12] Moreover, arterial stiffness and BP were negatively associated with cardiorespiratory fitness.[13] When considering the pathophysiological implications of vascular stiffening, it is also important not to overlook changes in the heart to which the blood vessels are coupled. In accordance with the concept of 'vascular–ventricular coupling' in that morphological and functional changes in the left ventricle and vasculature are closely coupled, we hypothesized that higher cardiorespiratory fitness is associated with the smaller age-related increases in arterial stiffness and BP, and that smaller increases attenuate LV

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remodelling. Accordingly, the aim of the present cross-sectional study was to determine the relationships between cardiorespiratory fitness, arterial stiffness, BP and LV structure in both pre- and post-menopausal women.

Methods

Subjects

A total of 159 premenopausal (young) and postmenopausal women (older) participated in the study (Table 1). The young participants were recruited from the University and the older participants were recruited from the community around the National Institute of Health and Nutrition (NIHN). The young participants were mostly university undergraduate or graduate students and the older participants were mostly clients of the health checkup for postmenopausal women in the NIHN. The participants had various physical activity levels, and none were regularly engaged in weight training.[14] None of the participants smoked and they were not taking steroids or hormone replacement therapy. None of the young women were taking oral contraceptives. None of the participants were on medication for hypertension, hyperlipidaemia or diabetes. The purpose, procedures and risks of the study were explained to each participant before inclusion, and all participants gave their written informed consent before participating in the study, which was approved by the Human Research Committee of the National Institute of Health and Nutrition. The study was carried out in accordance with the Declaration of Helsinki.

To assess the effects of cardiorespiratory fitness on arterial stiffness, BP and LV structure, participants were categorized into either low (unfit) or high (fit) cardiorespiratory fitness groups on the basis of peak oxygen uptake ($\dot{V}_{2\mathrm{peak}}$). The young and older women were divided into fit and unfit groups with median $\dot{V}_{2\mathrm{peak}}$ values of 33.9 and 29.5 ml kg^{-1} min^{-1}, respectively. This method is simple and straightforward. Moreover, these values are consistent with the reference values for the maximal oxygen uptake for health promotion by gender and age, as described by the Japanese Ministry of Health, Labor and Welfare to prevent lifestyle-related diseases.[15]

Before testing, the participants abstained from caffeine and fasted for at least 4 h (a 12-h overnight fast was used for determination of metabolic risk factors, arterial stiffness, wave reflection, BP and LV structure). The fitness assessment was performed after the other tests.

Arterial stiffness and BP

Pulse wave velocity (PWV) has been used as a non-invasive index of arterial stiffness and is reported to predict cardiovascular events.[16] Carotid-femoral PWV is widely used, although complicated techniques are required to obtain an accurate pulse wave.[17] Brachial-ankle pulse wave velocity (baPWV) has also been developed as a simple, non-invasive index of arterial stiffness and is reported to be correlated with carotid-femoral PWV.[18] Participants were studied under quiet resting conditions in the supine position. BaPWV and carotid augmentation index (AI), which are indexes of arterial stiffness and wave

Table 1 Participant characteristics

Variables	*Young*		*Older*		*P (two-way ANOVA)*		
	Unfit	*Fit*	*Unfit*	*Fit*	*Age*	*Fitness*	*Interaction*
N	49	50	30	30			
Age (year)	24 ± 5	23 ± 3	61 ± 7*	58 ± 5*	<0.001	<0.01	NS
Height (cm)	159.4 ± 5.6	162.9 ± 6.6†	155.9 ± 4.4*	155.6 ± 6.2*	<0.001	NS	NS
Weight (kg)	54.0 ± 8.4	55.0 ± 6.9	55.7 ± 7.9	52.0 ± 5.3*,†	NS	NS	<0.05
Body surface area (m^2)	1.54 ± 0.13	1.58 ± 0.12	1.55 ± 0.09	1.49 ± 0.1*,†	<0.001	NS	<0.05
BMI (kg m^{-2})	21.2 ± 2.8	20.7 ± 1.8	22.9 ± 3.2*	21.5 ± 1.8†	<0.001	<0.01	NS
Brachial SBP (mm Hg)	104 ± 9	107 ± 9	130 ± 22*	117 ± 15*,†	<0.001	<0.05	<0.001
Brachial DBP (mm Hg)	60 ± 7	60 ± 6	76 ± 11*	69 ± 8*,†	<0.001	<0.05	<0.01
Brachial MAP (mm Hg)	77 ± 8	78 ± 7	100 ± 17*	89 ± 11*,†	<0.001	<0.01	<0.001
Carotid PP (mm Hg)	38 ± 8	37 ± 7	60 ± 26*	49 ± 15†	<0.001	NS	<0.01
Plasma glucose (mg per 100 ml)	87 ± 6	88 ± 5	95 ± 7*	93 ± 10*	<0.001	NS	NS
Plasma insulin (μU ml^{-1})	5.6 ± 2.5	5.8 ± 2.7	4.7 ± 3.4	4.2 ± 2.6*	<0.01	NS	NS
Total cholesterol (mg per 100 ml)	181 ± 25	176 ± 29	212 ± 34*	219 ± 25*	<0.001	NS	NS
HDL cholesterol (mg per 100 ml)	65 ± 13	72 ± 14†	65 ± 14	73 ± 14†	NS	<0.01	NS
Triglycerides (mg per 100 ml)	65 ± 27	59 ± 23	87 ± 32*	77 ± 34*	<0.001	NS	NS
Peak oxygen uptake (ml kg^{-1} min^{-1})	29.9 ± 2.5	41.4 ± 4.6†	23.0 ± 3.8*	34.2 ± 3.2*,†	<0.001	<0.001	NS
Hypertension (%)	0	0	33*	13*	—	—	—
Hypercholesterolaemia (%)	0	0	63*	80*	—	—	—
Diabetes (%)	0	0	0	0	—	—	—

Abbreviations: ANOVA, analysis of variance; BMI, body mass index; DBP, diastolic blood pressure; HDL, high-density lipoprotein cholesterol; NS, not significant; PP, pulse pressure; SBP, systolic blood pressure.
Data are means ± s.d.
*$P<0.05$ vs young women in the same fitness group.
†$P<0.05$ vs unfit women in the same age group.

reflection, and BP were measured using a semi-automated oscillometric device (form PWV/ABI; Colin Medical Technology, Komaki, Japan) according to the method previously described.[18] The device records PWV, BP, electrocardiogram (ECG) and heart sounds simultaneously. ECG electrodes were placed on both wrists, and a heart sound microphone was placed on the left sternal border. The cuffs to measure baPWV were wrapped around both upper arms and ankles, and connected to a plethysmographic sensor that determines the volume pulse form. Volume waveforms were stored for a sampling time of 10 s with automatic gain analysis and quality adjustment. The time delay from the ascending point of the brachial artery waveform to the ascending point of each tibial artery waveform (ΔTa) was determined by the foot-to-foot method. The path lengths from the suprasternal notch to the arm (ΔDa), from the suprasternal notch to the femur (ΔDb) and from the femur to the ankle (ΔDc) were calculated to be $0.2195 \times H - 2.0734$, $0.5643 \times H - 18.381$ and $0.2486 \times H + 0.709$, respectively, where H is the participant's height in centimetre. The baPWV was calculated using the following formula: $(\Delta Db + \Delta Dc - \Delta Da)/\Delta Ta$ (cm s^{-1}). The right baPWV in each participant was used for subsequent analyses. The coefficient of variation for inter-observer reproducibility of baPWV was 4% in our laboratory.

Carotid AI, which is an index of wave reflections, was calculated as the ratio of amplitude of the pressure wave above its systolic shoulder to the total pulse pressure (PP) of carotid artery, as previously described.[13,19] Carotid AI has been an independent predictor of all-cause and cardiovascular mortality.[20] A multi-element tonometry sensor, consisting of 15 pressure-sensitive small elements aligned side by side, was coupled to the device. The carotid tonometry sensor is compact and lightweight and can be easily attached around the neck. The sensor element located manually at the centre of the carotid artery can be identified by screening the PP levels of the 15 elements, provided that the sensor element size is sufficiently small compared with the vessel diameter. The quality of the carotid pulse wave and the downward force were checked visually by carotid compression tonography, and pulse waves were recorded and stored over 30-s periods. The measured pressure waveform consists of both a 'forward' or 'incident' wave, and a 'reflected' wave that is returning from a peripheral site. The reflected wave is superimposed on the incident wave such that the pulse and systolic pressures are increased. This increase is defined as a pressure pulse AI, and it is calculated as the pressure wave above its systolic shoulder (ΔP) divided by PP.[19] The shoulder was defined as the first concavity on the upstroke of the wave that separates the initial systolic pressure rise from the late systolic peak. The carotid AI has been proposed as an indicator of the magnitude of wave reflections, which is closely linked to arterial stiffness.[19] In this study, carotid AI was used as a measure of the stiffness of the central arteries. As baseline levels of BP are subjected to hold-down force, the pressure signal obtained by tonometry was calibrated by equating the carotid MAP and diastolic blood pressure to the brachial artery value.[12,14] The coefficient of variation for inter-observer reproducibility of AI was 5% in our laboratory. Hypertension was defined as systolic blood pressure (SBP) $\geqslant 140$ or diastolic blood pressure $\geqslant 90$.

LV dimensions and mass

Immediately after measurement of arterial stiffness and BP, echocardiographical studies were carried out in each participant using an ultrasound machine equipped with a 2.5 MHz transducer (vivid *i*; GE Medical System, WI, USA). Ultrasound images were analysed using computerized image analysis software (Image J; National Institutes of Health, MD, USA). At least five measurements of M-mode images were taken at each segment, and the mean values were used for the analyses. The echocardiograms were obtained at rest with the participant in the left lateral decubitus position. Two-dimensional guided M-mode measurements of LV end-systolic dimension and LV end-diastolic dimension (LVEDD), interventricular septal thickness (IVS) and posterior wall thickness (PWT) were performed in accordance with the recommendations of the American Society of Echocardiography.[21] LV mass was calculated according to the regression equation of Devereux *et al.*:[22] $0.80 \times (1.04 \times (\mathrm{LVEDD} + \mathrm{IVS} + \mathrm{PWT})^3) - (\mathrm{LVEDD})^3 + 0.6$. LV dimensions and mass were normalized for the body surface area. RWT was calculated as twice the ratio of posterior wall thickness to the LV end-diastolic diameter.[23] The coefficient of variation for inter-observer reproducibility of LV dimensions was 7% in our laboratory.

Cardiorespiratory fitness

Cardiorespiratory fitness, assessed with $\dot{V}_{2\mathrm{peak}}$, was measured by an incremental cycle exercise test using a cycle ergometer (Monark, Varberg, Sweden). The incremental cycle exercise began at a work rate of 30 or 60 W (60 r.p.m.), and power output was increased by 15 W min^{-1} until the participants could not maintain the fixed pedalling frequency. The participants were encouraged during the ergometer test to exercise at the level of maximum intensity. The heart rate and rating of perceived exertion (RPE) were monitored minute by minute during exercise. Oxygen uptake (VO_2) was monitored during the last 30 s of each increase in work rate after the RPE reached 18. RPE was obtained using the modified Borg scale.[24] Participants breathed through a low-resistance two-way valve, and the expired air was collected in Douglas bags. Expired O_2 and CO_2 gas concentrations were measured by mass spectrometry (WSMR-1400; Westron, Chiba, Japan), and gas volume was determined using a dry gas meter (NDS-2A-T; Shinagawa Dev., Tokyo, Japan). The highest value of $\dot{V}_{2\text{peak}}$ during the exercise test was designated as $\dot{V}_{2\text{peak}}$.

Blood samples
Blood samples were taken after at least 10 h of overnight fasting to determine fasting glucose and insulin levels. In the same session, serum samples were withdrawn to determine fasting total cholesterol, high-density lipoprotein (HDL) cholesterol and triglyceride levels. Hypercholesterolaemia was defined as plasma total cholesterol $\geqslant$200 mg per 100 ml; diabetes was defined as fasting blood glucose $\geqslant$126 mg per 100 ml.

Body composition
Body composition was determined by dual-energy X-ray absorptiometry (Hologic QDR-4500; Hologic, Waltham, MA, USA) with participants in the supine position.

Statistical analyses
Statistical analyses were carried out with StatView (SAS Institute, Cary, NC, USA). Two-way analysis of variance (ANOVA) (age × cardiorespiratory fitness) and analysis of covariance (ANCOVA) were used to compare continuous variables, and a χ^2-test was used for categorical variables. When a significant *F*-value was obtained, Scheffe's *post hoc* test was used to identify significant differences among mean values. When young and older women were compared within the same activity group, the data were analysed by one-way ANOVA. Relations of interest were initially identified by simple regression analysis. Independent relations among the dependent variables were determined by multiple regression analysis. All data are shown as means ± s.d. Statistical significance was set *a priori* at $P<0.05$ for all comparisons.

Results

Plasma glucose, total cholesterol and triglyceride levels were higher ($P<0.01$) in older women compared with young women (Table 1). HDL cholesterol was significantly higher ($P<0.05$) in fit women compared with their age-matched unfit peers. Although the percentages of hypertension and hypercholesterolaemia were higher ($P<0.01$) in older compared with young women, there were no significant differences between fit and unfit older women. None of the participants had diabetes. In both age groups, $\dot{V}_{2\text{peak}}$ in the fit group was $\sim$11 ml^{-1} kg^{-1} min^{-1} higher than in the age-matched unfit peers.

Figure 1 illustrates the arterial stiffness, wave reflection and BP (baPWV, carotid AI and SBP) in the unfit and fit groups. Two-way ANOVA indicated a significant interaction between age and cardiorespiratory fitness in determining baPWV, carotid AI and BP ($P<0.01$). In both fitness groups, baPWV, carotid AI and SBP were higher ($P<0.01$) in older women than in young women. In the young women, there were no significant differences in either baPWV, carotid AI or SBP between the fit and the unfit women. In older women, baPWV, carotid AI and SBP in the fit group were significantly lower ($P<0.01$) than in their unfit peers. When ANCOVA was carried out using body mass index and HDL cholesterol as covariates, the difference remained statistically significant ($P<0.01$). Carotid PP was significantly higher ($P<0.01$) in unfit older women compared with the other groups (Table 1).

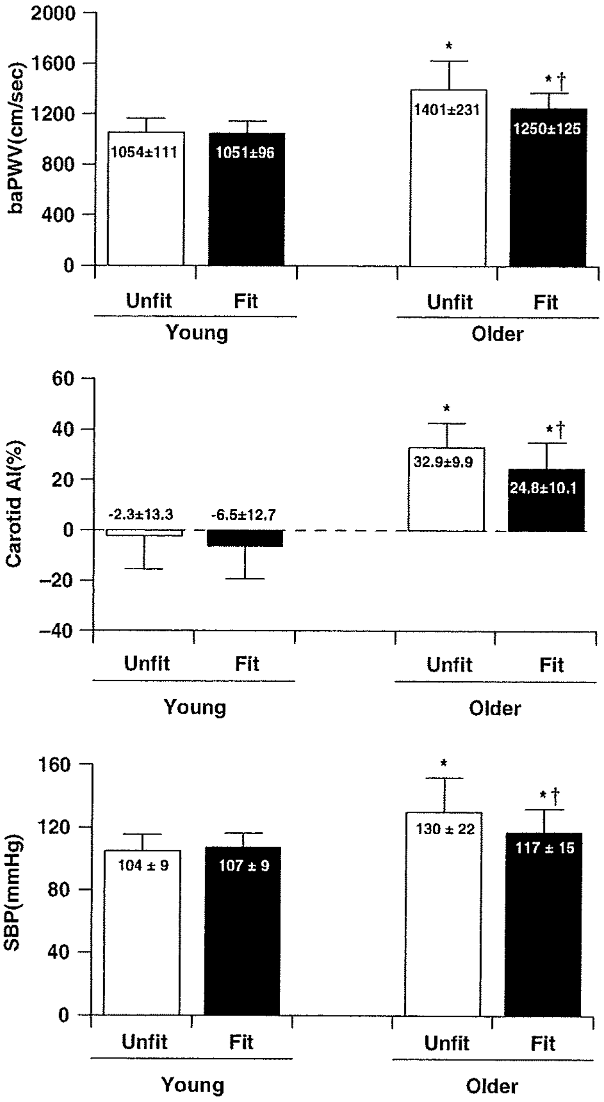

Figure 1 Arterial stiffness and BP in unfit and fit women. *$P<0.01$ vs young women in the same fitness group; †$P<0.01$ vs unfit women in the same age group. baPWV, brachial-ankle pulse wave velocity.

Left ventricular end-diastolic dimension was significantly greater (young; $P<0.01$, older; $P<0.05$) in the fit women compared with their age-matched unfit peers (Table 2). In both fitness level groups, IVS and PWT were higher in older women compared with the young women. In the young group, although LV mass index was larger in the fit women, there was no significant difference in the older group. Figure 2 illustrates the effects of age and cardiorespiratory fitness on LV structure (RWT). Two-way ANOVA indicated a significant interaction between age and cardiorespiratory fitness in determining RWT ($P<0.01$). In both fitness groups, RWT was larger ($P<0.01$) in older than in young women. In the young women, there were no significant differences in RWT between the fit and unfit groups. In older women, RWT in the fit group was significantly thinner ($P<0.01$) than in their unfit peers. When ANCOVA was carried out using body mass index and HDL cholesterol as covariates, the difference remained statistically significant ($P<0.05$). However, the difference in RWT was abolished after adjusting for baPWV or SBP.

Left ventricular hypertrophy was considered present when the LV mass indexes were $\geqslant 110\,\mathrm{g\,m^{-2}}$ for women.[22] Increased RWT was present when this ratio was $\geqslant 0.45$.[23] Normal geometry was present when LV mass index and RWT were normal, increased RWT and normal LV mass index identified concentric remodelling, increased LV mass index with normal RWT identified eccentric hypertrophy and increases of the two variables identified concentric hypertrophy.[25] In this study, older, fit women with LV concentric hypertrophy or remodelling ($N=8/30$) were significantly ($P<0.05$) fewer in number than was the case with unfit peers ($N=17/30$). Table 3 shows the arterial stiffness, BP and fitness parameters in individuals of different LV hypertrophy patterns. In the normal geometry group, baPWV, carotid AI and BP were higher ($P<0.01$) than in the concentric hypertrophy and remodelling group.

Univariate correlation analyses were carried out to determine which physiological variables were most closely associated with RWT. To eliminate the effect of age, the data were divided into young and older women. In older women, RWT was significantly related to SBP ($r=0.57$, $P<0.01$), MAP ($r=0.58$, $P<0.01$), DBP ($r=0.46$, $P<0.01$), carotid PP ($r=0.57$, $P<0.01$), baPWV ($r=0.46$, $P<0.01$), carotid AI ($r=0.29$, $P<0.05$) and $\dot{V}_{2\text{peak}}$ ($r=-0.32$, $P<0.05$). In young women, they were not significant correlations, except for weak correlation between RWT and SBP ($r=0.21$, $P<0.05$). RWT was not significantly related to body mass index and HDL cholesterol in both age groups. Figure 3 shows the relationships between RWT and selected correlates of interest in overall young and older women. In the overall study population, a multiple regression analysis showed that the association between RWT and baPWV was not significant after adjustment for age and SBP as covariates.

Discussion

Main findings

The main findings of this study were as follows. First, arterial stiffness and BP in fit older women were lower than in their unfit counterparts. Second,

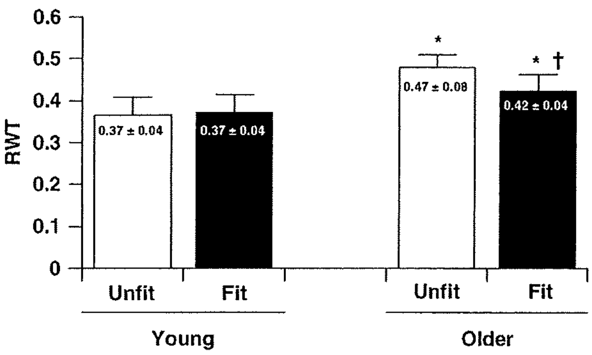

Figure 2 RWT in unfit and fit women. *$P<0.01$ vs young women in the same fitness group; †$P<0.05$ vs unfit women in the same age group. RWT, relative wall thickness.

Table 2 LV dimensions and mass

Variables	*Young*		*Older*	
	Unfit	*Fit*	*Unfit*	*Fit*
LVEDD ($\mathrm{mm\,m^{-2}}$)	29.0 ± 1.9	29.9 ± 2.0†	28.4 ± 2.7	30.5 ± 2.1†
LVESD ($\mathrm{mm\,m^{-2}}$)	17.7 ± 1.8	18.5 ± 1.8†	16.4 ± 1.9*	17.1 ± 1.7*
IVS ($\mathrm{mm\,m^{-2}}$)	5.14 ± 0.58	5.42 ± 0.50†	6.80 ± 1.45*	6.56 ± 0.98*
PWT ($\mathrm{mm\,m^{-2}}$)	5.47 ± 0.75	5.64 ± 0.68	6.70 ± 1.48*	6.35 ± 0.86*
LV mass index ($\mathrm{g\,m^{-2}}$)	76.0 ± 10.0	90.0 ± 16.9†	103.0 ± 36*	102.0 ± 21.8*
RWT	0.37 ± 0.04	0.37 ± 0.04	0.47 ± 0.08*	0.42 ± 0.04*,†

Abbreviations: IVS, interventricular septal thickness; LVEDD, left ventricular end-diastolic dimension; LVESD, left ventricular end-systolic dimension; PWT, posterior wall thickness; RWT, relative wall thickness.
Data are means ± s.d.
*$P<0.05$ vs young women in the same fitness group.
†$P<0.05$ vs unfit women in the same age group.

Table 3 Arterial stiffness, blood pressure and fitness parameters in participants of the different LV hypertrophy patterns

Variables	*Concentric hypertrophy*	*Concentric remodelling*	*Eccentric hypertrophy*	*Normal geometry*
N	12	19	10	118
baPWV ($cm\,s^{-1}$)	1450 ± 238	1309 ± 229	1124 ± 136†	1104 ± 150*
Carotid AI (%)	32.8 ± 12.0	21.7 ± 16.4	6.7 ± 19.1†	3.6 ± 19.0*
SBP (mm Hg)	141 ± 27	124 ± 17†	108 ± 8*	108 ± 11*
Peak oxygen uptake ($ml\,kg^{-1}$ per min)	27.3 ± 9.6	29.1 ± 6.2	40.4 ± 7.9*	33.6 ± 6.9†,‡

Abbreviations: AI, augmentation index; baPWV, brachial-ankle pulse wave velocity; SBP, systolic blood pressure.
Data are means ± s.d.
*$P<0.05$ vs concentric hypertrophy and remodelling group.
†$P<0.05$ vs concentric hypertrophy group.
‡$P<0.05$ vs eccentric hypertrophy group.

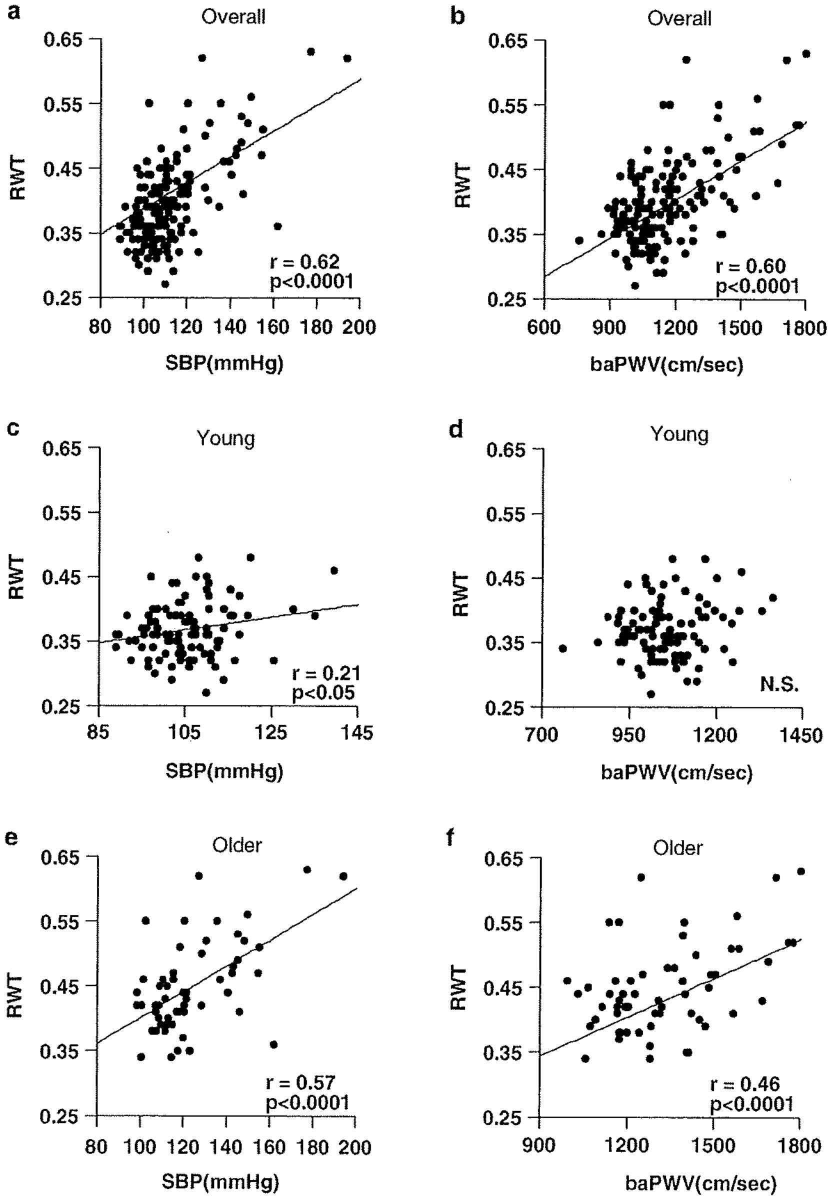

Figure 3 Relationships between RWT and systolic blood pressure (SBP) or baPWV overall (**a** and **b**), and in younger (**c** and **d**) and older (**e** and **f**) women. RWT, relative wall thickness; baPWV, brachial-ankle pulse wave velocity; NS, not significant.

RWT in fit older women were also lower than in their unfit counterparts. Third, RWT was strongly related to BP and arterial stiffness in older women. Fourth, there were no such differences and relationships in young women. These results suggest that higher cardiorespiratory fitness attenuates arterial stiffening and LV concentric remodelling in older women.

Arterial stiffness

Previous studies have indicated that age-related arterial stiffening is attenuated in fitter adults,[11,12] and that central arterial stiffness and BP are negatively associated with cardiorespiratory fitness.[13] We too found that older, fit women showed lower baPWV and AI when compared with older, unfit peers. Cardiorespiratory fitness is a major determinant of overall physiological functional capacity, and low levels of cardiorespiratory fitness have been identified as a risk factor for cardiovascular and all-cause mortality.[9] Thus, the present and previous findings suggest that arterial stiffness may be one factor responsible for the inverse relationship between premature mortality and cardiorespiratory fitness in those who are middle-aged and older.

In this study, older, fit women showed lower arterial stiffness. One possible reason for this finding is that BP does not increase as much with age in women who are very fit. Indeed, we found that the differences in baPWV and AI between groups were qualitatively similar to the differences in BP (Figure 1). Another possibility is that higher cardiorespiratory fitness minimizes age-related structural changes in the arterial wall. In this regard, the endurance-trained state has been shown to be associated with an elevated overall content of elastin and a reduced calcium content,[26] and reduced formation of advanced glycation end products and collagen cross-linking in the arterial wall.[27] A third possibility is that higher cardiorespiratory fitness may act to maintain endothelium-dependent vasodilation with age, as previously reported.[28]

LV structure

LV wall thickness increases with age not only in individuals with hypertension but also in normotensive adults.[4] Moreover, physiological hypertrophy ('the athlete's heart'), characterized by an increase in LV chamber size and mass, is observed in adults with a high level of cardiorespiratory fitness.[29] Given this, it is reasonable to hypothesize that both age and cardiorespiratory fitness are associated with increased LV wall thickness and mass. Gates *et al.*[30] reported that the highest mean values for these LV characteristics were observed in older endurance-trained men, suggesting an additive effect of ageing and exercise behaviour. In contrast to the previous findings, our results indicated that RWT in old, less fit women was significantly thicker than in fit peers. Moreover, older, fit women with LV concentric hypertrophy or remodelling ($N=8/30$) were fewer in number than was the case in less fit peers ($N=17/30$). Taken together, in contrast to the men's results, LV hypertrophy and remodelling are attenuated in older women with a high level of cardiorespiratory fitness. These sex-specific differences may be partly explained by concentrations of endogenous anabolic and sex hormones.[31]

Long-term athletic training produces alterations in cardiac structure that result in an increase in calculated LV mass without concentricity.[29] Mortality and the frequency of cardiovascular events are highest in patients with concentric hypertrophy,[23] which is often a maladaptive response to provocative stimuli such as hypertension and arterial stiffness. In this study, fit young women had higher LV mass than their unfit counterparts, without LV concentricity; neither fit nor unfit young women had high levels of BP or arterial stiffness. Thus, we thought that although fit young women had a higher LV mass, this is not unfavourable hypertrophy induced by provocative stimuli.

What physiological mechanisms might explain attenuating LV concentric remodelling in fit older women? LV remodelling is commonly conceptualized as an adaptive response to increased cardiac afterload caused by vascular loading such as arterial stiffening and hypertension. The results of *in vitro* studies indicate that mechanical stretching is the primary stimulus responsible for induction of increased cardiac myocyte protein synthesis and hypertrophy.[32] We therefore hypothesized that removal of the excess mechanical stimulus applied to the LV is one of the mechanisms responsible for attenuation of remodelling. Indeed, in this study, when ANCOVA was carried out using baPWV and SBP as covariates, the difference in RWT was abolished. Moreover, arterial stiffness and BP were strongly and significantly related to RWT in older women but not in younger women, which is consistent with the previous report by Schillaci *et al.*[33] Thus, high cardiorespiratory fitness is associated with lower arterial stiffness, BP and LV relative wall thickness in older women. Other possible mechanisms may be that regular aerobic exercise modulates selective age-associated impairments in the autonomic nervous system[34], suppression of myocardial collagen cross-linking[35] and attenuation of gene expression of atrial natriuretic peptides.[36] It is possible that the maintenance of higher cardiorespiratory fitness contributes to the attenuation of age-related LV remodelling by removal of the various factors that cause loading of the LV.

Clinical implications

Epidemiological studies have indicated that highly fit men and women have a lower incidence of cardiovascular disease in comparison with their sedentary peers.[37] Although the mechanisms underlying this protective effect probably include favourable changes in traditional risk factors,[38] an additional possibility is that a high level of cardiorespiratory fitness is associated with attenuated LV remodelling through the control of increases in arterial stiffening, particularly in middle-aged and older adults. A recent study in hypertensive rats indicated that exercise training attenuated the development of heart failure and also increased survival and attenuated LV concentricity without a reduction in LV mass.[39] Similar to these findings, RWT in our fit older group was thinner than in the unfit group, without a reduction in the LV mass. These results suggest that exercise has a direct beneficial effect on LV concentric remodelling.

Antihypertensive treatment also reduces the LV mass and decreases the prevalence of LV hypertrophy and concentric remodelling.[40] However, unlike antihypertensive drugs, which are costly, have effects that are largely limited to BP control, and often have adverse effects, aerobic exercise training is a relatively safe and inexpensive form of therapy with favourable effects on a broad spectrum of cardiovascular disease antecedents and outcomes. Our findings suggest that, in addition to antihypertensive medications[40] and salt restriction,[41] the maintenance of higher cardiorespiratory fitness may also be effective in partial attenuation of LV remodelling in middle-aged and older women. Therefore, the improvement of cardiorespiratory fitness may be an important tool for the primary prevention of cardiovascular disease.

Limitations

This study has several limitations. First, as an initial approach to determine the relation between cardiorespiratory fitness, arterial stiffness, BP and LV remodelling, we used a cross-sectional study design. Owing to the design of this study, we could not evaluate individual changes in age-related arterial stiffness, BP and LV structure. Although fitter older women had both lower BP and lower PWV than their unfit counterparts, the cross-sectional design of the study does not allow us to clarify whether fitness favourably affects BP (and consequently stiffness) or stiffness (and consequently BP). As this type of study design has a number of well-recognized limitations, we attempted to isolate the influence of cardiorespiratory fitness as much as possible. To do so, both young and older women were carefully matched for differences in $\dot{V}_{2\mathrm{peak}}$ between the groups of fit and unfit individuals (11 ml^{-1}kg^{-1}min). In addition, to isolate the effect of cardiorespiratory fitness *per se*, individuals taking drugs for hypertension, diabetes or hyperlipidaemia were excluded from the study. However, the results of this cross-sectional study must be confirmed in future long-term prospective studies.

Second, the estimation of LV mass may not be accurate because M-mode echocardiography does not consider LV long-axis length. On the other hand, there are insubstantial differences in the LV internal diameter, wall thickness and calculated RWT, irrespective of the method used. Indeed, a previous study indicates that RWT increases with age, whereas LV mass does not change.[4] Consistent with the previous study, we observed an age-related increase in RWT. In contrast to that study, we observed age-related increases in the LV mass. Therefore, although the M-mode calculation is sufficient to assess RWT, the calculations of LV mass should be confirmed by the two-dimensional area-length method[42] and magnetic resonance imaging.[43]

Third, we used baPWV as a measure of arterial stiffness. The value of baPWV includes stiffness derived from the combination of large arteries and peripheral arteries. Compared with central elastic arteries, peripheral arteries are generally considered to be of less clinical significance. However, baPWV is strongly related to aortic PWV[18] and may provide qualitatively similar information to central arterial stiffness. Nevertheless, the results of baPWV determinations need to be confirmed by aortic PWV in the future.

What is known about the topic:

- Arterial stiffness and blood pressure (BP) increase with age[1] and are negatively associated with cardiorespiratory fitness.[13]
- Left ventricular relative wall thickness also increases with age.[4]
- Whether or not there is a relationship between left ventricular (LV) remodelling and the lower arterial stiffness and BP in women with a high level of cardiorespiratory fitness is not clear.

What this study adds:

- Higher cardiorespiratory fitness is associated with lower arterial stiffness and BP and attenuated LV concentric remodelling in older women.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgements

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ORIGINAL ARTICLE

Elderly oarsmen have larger trunk and thigh muscles and greater strength than age-matched untrained men

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Abstract To evaluate whether regularly performed rowing exercise affects the trunk muscles size and function, and to examine the effect of rowing exercise on thigh muscle size and function in elderly rowers, we compared the cross-sectional area (CSA) and strength of these muscles in elderly male rowers and in age-matched untrained men. Participants were 16 elderly rowing-trained men (ROW age, 67.8 ± 2.3 years) and 18 elderly untrained men (CON 66.2 ± 3.0 years). CSA was measured by MRI in the trunk and thigh muscles. Isometric trunk flexion force and leg extension power were measured. ROW had a 20% larger total trunk muscle CSA than CON ($P < 0.01$); rectus abdominis was 27% larger, psoas major 64% larger, and erector spinae 14% larger in ROW than in CON ($P < 0.05$–0.001). Isometric trunk flexion force was related to the CSA of the rectus abdominis ($r = 0.777$, $P < 0.001$) and psoas major ($r = 0.694$, $P < 0.001$), and was 42% larger in ROW than in CON ($P < 0.001$). However, force adjusted for the CSA of the muscles did not differ significantly between CON and ROW. In ROW, the CSA was 13% larger in the total thigh muscles ($P < 0.01$), and leg extension power was 43% higher than in CON ($P < 0.001$). These results suggest that rowing exercise is a favorable training modality for the trunk muscles, especially psoas major and that it improves thigh muscle size and function in elderly men.

Keywords Rowing · Elderly · Trunk muscles · MRI

Introduction

With advancing age, muscle size decreases more in the trunk and thigh than in other sites (Kanehisa et al. 2004; Miyatani et al. 2003; Ishida et al. 1997). The muscles of the thigh play an essential role in transferring the body in various movements such as walking and standing up from a chair (Kim et al. 2000; Hughes et al. 1996). The muscles of the trunk are important for raising the leg when climbing stairs and stabilizing the body (Masuda et al. 2002; Penning 2000; Bogduk et al. 1992; Krebs et al. 1992). Because the age-related decrease in the trunk and thigh muscles mass is associated with the risk of falls and disability in activities of daily living in elderly people (Grabiner et al. 2008; Lamoureux et al. 2001; Rubenstein et al. 2000), it is important to prevent weakness of these muscles.

Rowing exercise involves almost all muscles of the body (Secher 1983). The trunk and thigh muscles are also used in the rowing motion (Rodriguez et al. 1990; Hosea et al. 1987). Rowers extend their legs in the first half of the rowing phase and flex their arms in the second half. Because it links the legs and the arms, the trunk performs much work by swinging backward in the middle of the drive phase. The leg, trunk, and arm motions account for

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about 40, 50, and 10% of the total rowing power, respectively (Tachibana et al. 2007). Yoshiga et al. (2002a, b) demonstrated that elderly oarsmen have larger knee extensor muscles and higher aerobic capacity than age-matched sedentary men. We hypothesized that elderly oarsmen also have larger trunk muscles.

To evaluate whether regularly performed rowing exercise affects the trunk muscle size and function, we compared the cross-sectional area (CSA) of trunk muscles in elderly male rowers and age-matched untrained men, and we examined the relationship between thigh muscle size and function in elderly male rowers.

Methods

Thirty-four healthy men aged 63–74 years participated in this study (Table 1). The subjects comprised a control group (CON; $n = 18$), who were confirmed by a questionnaire as not having performed any regular exercise for >30 min more than twice per week, and a rowing-trained group (ROW; $n = 16$), who had rowed 2–3 times per week for more than 3 years, with each session lasting 60–120 min on the water or on a rowing ergometer (12–16 km per session). ROW had rowed for 3.9 ± 0.3 years in their college days; they restarted rowing after retirement and had rowed for 7.9 ± 3.3 years since restarting. The amount of daily physical activity did not differ significantly between ROW and CON except for the rowing training measured by a uniaxial accelerometer (Life-Corder, Suzuken Co., Nagoya, Japan) (CON 8,739 ± 3,696 steps/day and 1,998 ± 213 kcal/day; ROW, 8,876 ± 2,775 steps/day and 2,086 ± 151 kcal/day, unpublished data). The two groups did not differ significantly on age, height, weight, or body mass index (BMI), but fat-free mass (FFM) was significantly higher in ROW than in CON ($P < 0.05$). None of the subjects had low-back pain, such as chronic low-back pain, lumbar hernia, or herniated lumbar disk. For this study, we calculated that a sample size of 16 would achieve more than 80% power with a significance level (alpha) of 0.05. After receiving a detailed explanation of the purpose, procedures, and risks of the study, the subjects gave their written informed consent before participating in the study, which was approved by the Human Research Ethics Committee of the Faculty of Sport Sciences of Waseda University. The study was performed in accordance with the guidelines of the Declaration of Helsinki 2006.

Table 1 Subjects' characteristics

	CON $n = 18$	ROW $n = 16$
Age (years)	66.2 ± 3.0	67.8 ± 2.3
Height (cm)	167.1 ± 5.1	169.8 ± 3.2
Weight (kg)	67.5 ± 11.6	70.2 ± 8.2
BMI (kg/m^2)	24.1 ± 3.9	24.3 ± 2.8
Fat free mass (kg)	51.9 ± 6.2	55.7 ± 4.0*
Cross-sectional area (cm^2)		
Whole trunk	556 ± 144	574 ± 121
Total skeletal muscle	132 ± 23	158 ± 20**
Rectus abdominis	12.5 ± 3.5	15.9 ± 3.3**
Oblique abdominal	49.9 ± 9.5	55.3 ± 7.1
Psoas major	15.2 ± 3.0	24.9 ± 6.5***
Erector spinae	46.7 ± 9.9	53.1 ± 7.6*
Quadratus lumborum	7.5 ± 2.6	8.6 ± 2.9
Whole thigh	355 ± 74	375 ± 51
Total skeletal muscle	253 ± 39	285 ± 33*
Quadriceps femoris	120 ± 19	137 ± 18*
Sartorius	6.5 ± 1.2	7.9 ± 1.4**
Adductor	76 ± 23	81 ± 14
Hamstrings	50 ± 12	59 ± 9
Strength		
Trunk flexion force (N)	315 ± 82	447 ± 62***
per RA and PM (N/cm^2)	11.5 ± 1.5	11.3 ± 1.7
Leg extension power (W)	928 ± 265	1,324 ± 232***
per QF (W/cm^2)	7.6 ± 1.4	9.7 ± 1.2***

Values are expressed as mean ± SD. *BMI* body mass index, *RA* rectus abdominis; *PM* psoas major, *QF* quadriceps femoris. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$ versus CON

Body composition

Body composition was performed using various techniques according to standard procedures. All measurements were performed on the same morning after a 12-h fast. Height was measured to the nearest 0.1 cm (YL-65, Yagami, Inc., Nagoya, Japan). Body weight and the percentage of body fat were measured to the nearest 0.1 kg and 0.1%, respectively, using an electronic body composition scale (Inner Scan BC-600, Tanita Co., Tokyo, Japan). BMI was calculated by dividing body weight in kilograms by height in meters squared (kg/m^2). FFM was calculated as body weight minus body fat weight.

CSA of muscles

The CSA of the trunk and thigh muscles was measured with MRI (Signa 1.5T, General Electric Co., Milwaukee, WI, USA) using a T1-weighted spin-echo and axial-plane sequence with a slice thickness of 10 mm with a repetition time of 500 ms and an echo time of 13.1 ms. Scanning of the cross-sectional images was performed at the L3–4 level and at the middle of the thigh, defined as midway between the greater trochanter and the lateral femoral condyle. Subjects were positioned supine with the hands placed on the abdomen and the knee flexed. During the scan, the subject was asked to hold his breath for about 30 s after inhalation. The magnetic resonance images were transferred to a computer and the CSA of the trunk and thigh muscles was determined using image analysis software (Slice-o-matic, Tomovision, Montreal, Canada) (Fig. 1a). We analyzed the sum CSA of the right and left rectus abdominis, oblique abdominal, psoas major, erector spinae, quadratus lumborum, quadriceps femoris, sartorius, adductors, and hamstrings. All scans and analyses were performed by the same investigator, and the coefficient of variation was within 0.4% for the CSA of each muscle.

Isometric trunk flexion force

The maximal voluntary isometric trunk flexion force of all subjects was measured with a specially designed dynamometer (Aptec, Osaka, Japan). Subjects wore a vest with a hook on the back and were seated in the apparatus keeping the hip joints flexed at 90°, the knee joints at 120° and the ankle at 60° on the footplate. Subjects were connected to the apparatus through a dynamometer with the hook of the vest while they folded their arms on the chest. Before the test, subjects performed adequate warm-up, comprising stretching and 2–3 submaximal contractions to become familiar with the test procedure. The subjects performed 2–3-s maximal voluntary isometric contraction three times, with at least 3 min of rest between trials to avoid any fatigue effects. If the difference between the two values of force was more than 10% of the higher one, the force was measured once more. The torque data during each task were amplified by a strain amplifier (DPM-611A711B, Kyowa, Tokyo, Japan) and A/D converted (Power Lab/16SP, AD Instruments, Sydney, Australia) into a personal computer at 100 Hz with a low-pass filter (cutoff frequency: 20 Hz). The highest value of the 2–3 force measurements was used in the analysis. The measurements were taken twice with 7–10 days in between in six subjects to assess the test–retest reliability. The intraclass correlation coefficient was 0.83 for isometric trunk flexion force, and no significant difference in force was observed between the first and second measurement ($P = 0.330$).

Leg extension power

Maximal bilateral leg extension power was determined as described previously (Kawakami et al. 1993) on a dynamometer (Anaeropress 3500, Combi Co., Tokyo, Japan). This movement involves knee and hip extensions in a coordinated manner. Subjects assumed a seated position with back supported. The hips, knees, and ankles were flexed 90° with the arms resting on a bar. Before the test, the subjects performed adequate warm-up, comprising

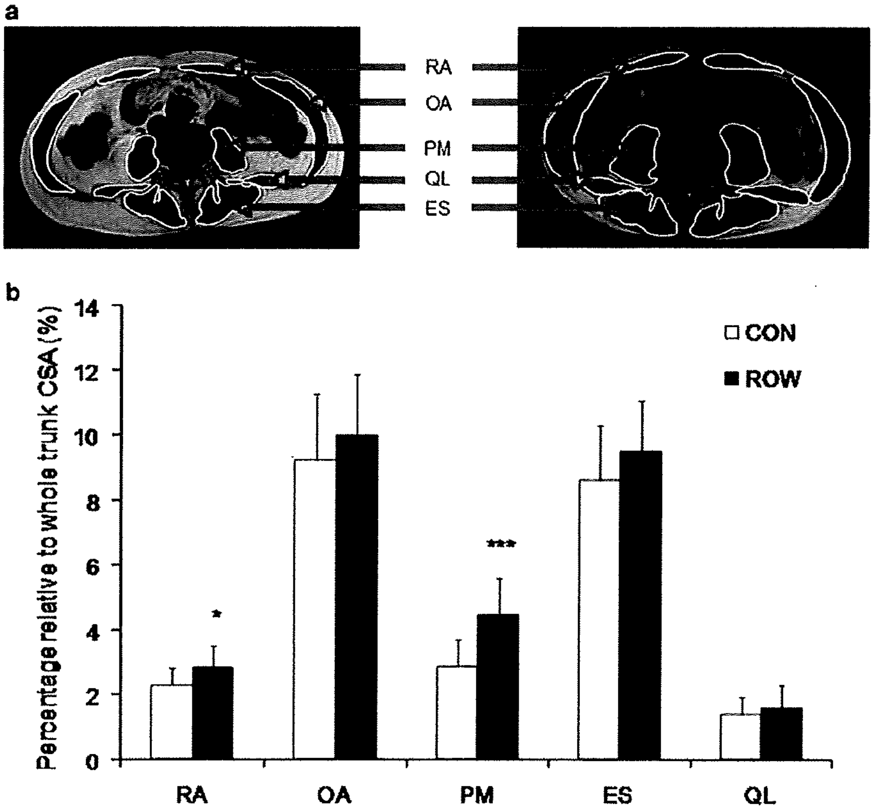

Fig. 1 **a** Magnetic resonance imaging of the trunk area obtained at the L3–4 level of CON (*left*) and ROW (*right*). **b** The percentages of muscle cross-sectional area to whole trunk area. *RA* rectus abdominis, *OA* oblique abdominal, *PM* psoas major, *ES* erector spinae, *QL* quadratus lumborum. * $P < 0.05$, *** $P < 0.001$ versus CON

stretching and 2–3 submaximal contractions to become familiar with the test procedure. The subjects were then instructed to press five times at a 20-s interval as hard as they could in a horizontal direction against the plate and to continue the movement until both legs were extended fully. The velocity of the movement was measured using a rotary encoder attached to a wheel that set a constant load to the footplate through a wire. The bilateral leg extension power (W) was the set load (N) times the velocity (m/s). This apparatus is suitable for evaluating bilateral leg extension power in healthy people, based on evaluation in individuals aged 6–90 years (Yoshiga et al. 2002b).

Statistical analysis

Values are expressed as mean ± SD. Statistical analyses were performed using SPSS 15.0 J for Windows (SPSS Inc., Chicago, IL, USA). The results of Kolmogorov–Smirnov tests indicated that all variables were normally distributed ($P > 0.1$). Student's t test was used to evaluate differences between CON and ROW. A two-way ANOVA was used to test for interaction effects between the group and CSA on each side of the body for the two groups. Where appropriate, the Tukey test was used to locate the source of the significant differences. Linear regression analysis was used to evaluate the relationships between strength and muscle CSA. Stepwise multiple linear regression analysis was used to evaluate the relationships between isometric trunk flexion force or leg extension power and age, height, body mass, and muscle CSA. The level of significance was defined as a P value of less than 0.05.

Results

The whole trunk CSA did not differ significantly between CON and ROW ($P = 0.729$; Table 1). By contrast, total trunk muscle CSA was 20% larger in ROW than in CON ($P < 0.01$; Table 1). The CSAs of the rectus abdominis, psoas major, and erector spinae were larger by 27, 64, and 14%, respectively, in ROW than in CON ($P < 0.05$–0.001; Table 1). The percentages of the CSAs of the rectus abdominis and psoas major relative to the whole trunk CSA were higher in ROW than in CON ($P < 0.05$, 0.001; Fig. 1b). The CSA of the psoas major per whole trunk muscle CSA was also 33% larger in ROW than in CON (15.6 ± 2.4 vs. 11.7 ± 2.5%, $P < 0.001$). Left- and right-muscle CSA symmetries were observed in the rectus abdominis, oblique abdominal, and erector spinae. However, asymmetry was observed in the left and right psoas major and quadratus lumborum. There was a significant effect of rowing that was independent of side ($P < 0.05$; Table 2).

Isometric trunk flexion force correlated significantly with the CSAs of the total trunk muscles, rectus abdominis, oblique abdominal, psoas major, erector spinae, quadriceps femoris, sartorius, adductors, and hamstrings ($r = 0.462$–0.777, $P < 0.05$–0.001; Fig. 2). In the stepwise multiple linear regression analysis that included the CSAs of the rectus abdominis, oblique abdominal, psoas major, erector spinae, quadriceps femoris, sartorius, adductors, and hamstrings, only the CSAs of the rectus abdominis and psoas major explained a portion of isometric trunk flexion force (15.2 and 6.0%, respectively). The isometric trunk flexion force was 42% higher in ROW than in CON ($P < 0.001$; Table 1). However, isometric trunk flexion force per CSA (cm^2) of the rectus abdominis and psoas major did not differ significantly between CON and ROW ($P = 0.753$; Table 1).

The thigh CSA did not differ significantly between CON and ROW ($P = 0.373$; Table 1). The CSAs of the thigh muscles were larger in ROW than in CON. In ROW, the CSA was 13% larger in the total thigh muscles, 14% larger in the quadriceps femoris, 20% larger in the sartorius, and 17% larger in the hamstrings ($P < 0.05$–0.01; Table 1). However, the CSAs of the quadriceps femoris and sartorius

Table 2 Trunk muscles CSA symmetry

	CON ($n = 18$)		ROW ($n = 16$)		P (two-way ANOVA)		
	Right	Left	Right	Left	Group	Side	Interaction
Rectus abdominis	6.0 ± 1.7	5.7 ± 1.3	6.5 ± 1.2	6.5 ± 1.4	0.150	0.496	0.500
Obliques abdominal	24.2 ± 4.1	24.7 ± 5.8	25.6 ± 4.1	25.9 ± 4.2	0.395	0.446	0.884
Psoas major	11.0 ± 2.0	11.1 ± 2.0	16.9 ± 3.9	18.0 ± 3.9	<0.001	0.033	0.106
Erector spinae	20.2 ± 3.9	20.0 ± 3.7	22.0 ± 3.0	21.9 ± 2.9	0.112	0.800	0.949
Quadratus lumborum	5.5 ± 1.7	5.9 ± 1.7	6.0 ± 2.1	6.9 ± 1.8	0.226	0.006	0.307
Quadriceps femoris	60.7 ± 8.9	59.7 ± 10.5	69.1 ± 8.7	68.3 ± 9.6	0.011	0.274	0.897
Sartorius	3.3 ± 0.7	3.2 ± 0.7	4.0 ± 0.7	3.9 ± 0.8	0.006	0.582	0.960
Adductor	38.4 ± 10.7	37.7 ± 11.5	40.7 ± 7.6	39.9 ± 7.5	0.494	0.296	0.959
Hamstrings	25.1 ± 6.2	25.7 ± 6.3	29.5 ± 4.5	29.5 ± 4.6	0.033	0.472	0.520

All measurements are in cm^2. Values are expressed as mean ± SD

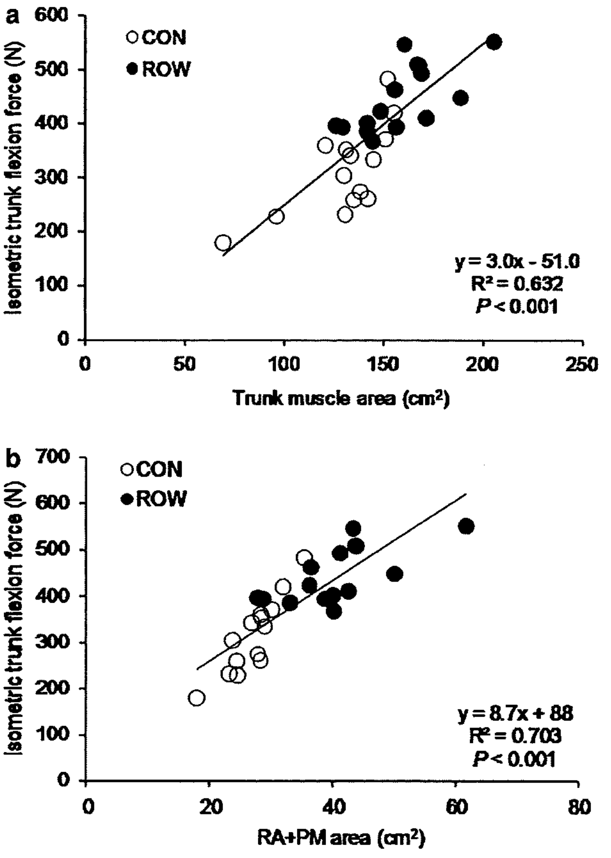

Fig. 2 Relationship between isometric trunk flexion force and (a) trunk total muscle area, (b) rectus abdominis (*RA*) area, and psoas major (*PM*) area

per total thigh skeletal muscle CSA did not differ between the two groups. Left and right muscle CSA symmetries were observed in all thigh muscles in all subjects (Table 2).

Leg extension power correlated significantly with the CSAs of the rectus abdominis, oblique abdominal, psoas major, erector spinae, quadriceps femoris, sartorius, and hamstrings ($r = 0.445$–0.747, $P < 0.01$–0.001). In the stepwise multiple linear regression analysis that included the CSAs of the rectus abdominis, oblique abdominal, psoas major, erector spinae, quadriceps femoris, sartorius, and hamstrings, only the quadriceps femoris CSA explained a portion of leg extension power. Leg extension power was 43% higher in ROW than in CON ($P < 0.001$; Table 1). After adjusting for the CSA of the quadriceps femoris, leg extension power was 29% higher in ROW than in CON ($P < 0.001$; Table 1).

Discussion

The primary finding was that the size of the trunk muscles, especially psoas major, was larger in elderly oarsmen than in age-matched sedentary men. Elderly oarsmen had better trunk muscle function than did elderly sedentary men. ROW had also a larger quadriceps femoris CSA and greater leg extension power than CON (Table 1). These results confirmed the findings of Yoshiga et al. (2002b), who showed that older oarsmen possess a larger leg extensor area and greater leg extension power than sedentary men. These results provide further evidence that regularly performed rowing exercise favorably affects muscle mass and function in elderly men.

In the rowing motion, the trunk generates about 50% of the total rowing power (Tachibana et al. 2007). A recent study indicated that trunk lean soft tissue mass measured by dual-energy X-ray absorptiometry was significantly greater in senior rowers than in senior controls (Sanada et al. 2009), but it was unclear which muscles in the trunk were larger in the rowers. We expected to find differences between CON and ROW in the trunk region, especially in the back muscles (e.g., erector spinae and quadratus lumborum) considering that the rowing motion involves conscious recruitment of these back muscles. We used MRI to compare the CSA of trunk muscles in elderly male rowers and age-matched untrained men. Contrary to our expectation, although the absolute values for the back muscles differed between groups, there was no difference when they were expressed as percentages of the whole trunk CSA and total trunk muscle CSA (Table 1; Fig. 1b). By contrast, of the trunk muscles, the psoas major CSA differed the most between CON and ROW, and the rectus abdominis size in ROW expressed both as an absolute value and as a percentage relative to the whole trunk CSA was second (Table 1; Fig. 1b). These results suggest that rowing exercise affects the trunk flexor muscles more than the extensor muscles in elderly men.

The type II muscle fiber number and size decreases with age, leading to a progressive decrease in the type II-to-type I fiber area ratio, which is reflected in an age-associated decrease in the muscles strength (Lexell et al. 1988; Larsson et al. 1979; Tomonaga 1977). The percentage of Type I fibers are greater in trunk extension muscles than in trunk flexion muscles in young to middle-age people (Marzani et al. 2005; Mannion 1999). Thus, aging may have little influence on trunk extensor muscles, and these muscles might be maintained by daily physical activities, regardless of the aging process, without any special exercise training. This might explain why we observed no differences in the back muscles between CON and ROW, as we had expected.

In this study, ROW had a larger psoas major CSA than CON. Psoas major size declines with aging, and this has important implications for walking and stair climbing ability, and falls prevention in older adults (Masuda et al. 2002; Kim et al. 2001; Kuno 2000). The psoas major is recruited during hip joint flexion and as a stabilizer of the hip and lumbar region (Penning 2000; Bogduk et al. 1992), and is thus important for balance when standing and walking. During aging, the size of the psoas major declines more than that of the quadriceps femoris, and the CSA of the psoas major is 50% smaller in people in their 60 s than in their 20 s (Takahashi et al. 2006; Kuno 2000). The psoas major CSA in CON in our study was similar to that observed in sedentary men age 60 years and older (Kuno 2000). By contrast, the psoas major CSA in ROW in our study was similar to that observed in sedentary men aged in their 30 s. Therefore, the larger psoas major size resulting from habitual rowing exercise may help older people maintain the ability to perform activities of daily life.

The larger psoas major and rectus abdominis muscle sizes in ROW were significantly related to better muscle function. Because psoas major and rectus abdominis are trunk flexor muscles, we measured the isometric trunk flexion force to evaluate the function of these muscles. The stepwise multiple linear regression analysis showed that only the CSAs of the rectus abdominis and psoas major explained a portion of isometric trunk flexion force, suggesting that isometric trunk flexion force is related to the function of the psoas major and rectus abdominis. However, isometric trunk flexion force per muscle CSA did not differ between the two groups (Table 1), suggesting that the greater muscle function of the psoas major and rectus abdominis observed reflects the larger CSAs of these muscles as a result of regular rowing exercise.

The loss of thigh muscles also impairs activities of daily living for older people (Rubenstein et al. 2000; Lamoureux et al. 2001). Yoshiga et al. (2002b) reported greater leg extensor muscle area and bilateral leg extension power in oarsmen than in age-matched sedentary men. In our study, similar to the findings of Yoshiga et al., ROW had larger quadriceps femoris CSA and greater leg extension power. We also found larger hamstring CSA in ROW than in CON. However, the CSAs of the leg extensor and flexor muscle CSA per total thigh skeletal muscle CSA did not differ between the two groups, indicating that each of the thigh muscles was larger in ROW than in CON and that, in ROW, no specific thigh muscles were affected more by rowing exercise. These results suggest that regularly performed rowing exercise has a positive effect by preventing the age-related decrease in the size of leg extensor and flexor muscles.

Sweep rowing is a type of rowing in which rowers use a single oar. In sweep rowing, each rower is numbered by boat position and is assigned to one side of the boat: a bow side person rows on the right side of the boat and a stroke side person rows on the left side. Thus, a rower might perform asymmetrical exercise during sweep rowing. Parkin et al. (2001) observed left and right asymmetry in the electromyography activity of the lumbar erector spinae muscle groups during trunk extension tests among young oarsmen and that this asymmetry could be related to low-back pain in oarsmen. In our study, we observed right and left asymmetry in psoas major and quadratus lumborum in all subjects; ROW had larger differences between left and right muscle CSA than did CON, but none of ROW reported low-back pain. The asymmetry observed in CON could be derived from the side dominance of the body. However, it is unclear as to the relationship between the side dominance and left- and right-asymmetry of muscle mass and strength. Further research will be required to investigate this relationship.

The physical activity and public health guidelines released by the American College of Sports Medicine and the American Heart Association recommend both aerobic and muscle-strengthening activity for older people (Nelson et al. 2007). Aerobic exercise should be based on exercises that use large muscle groups, is rhythmic and aerobic, can be done over prolonged periods of time, and is associated with a relatively low risk of injury. Rowing exercise involves almost all muscles of the body and rhythmic muscle extensions and flexion in the arms, trunk, and legs (Secher 1983). Thus, rowing exercise meets all the criteria and is recommended as aerobic exercise in the American College of Sports Medicine Position Stand (1998). Moreover, rowing is unlikely to induce serious damage or injury to the knee because the body mass is supported by the seat of the boat or ergometer. Thus, rowing is a safe and simple exercise for older or obese people. Our results showed that regular rowing exercise favorably affects muscle mass and function in elderly men and suggest that rowing exercise is a safe and effective exercise for preventing the age-related decrease in muscle size and function, and lifestyle-related diseases.

Our investigation has some limitations. First, we analyzed one-slice MRI images to assess muscle size, and the data were not always reflected in muscle volume. Second, we did not measure trunk extension force or leg flexion power because we could not ensure the subject's safety and the reliability of the data. In elderly people, trunk extension force measurement has a higher risk of low-back pain than trunk flexion force, and leg flexion power measurement has a risk of muscle strain. Third, this study was a cross-sectional study and we could not demonstrate that regularly performed rowing exercise actually maintains or increases the psoas major muscle size and function in elderly sedentary people independent of changes in body composition and a background of sport and exercise participation.

Conclusions

Elderly oarsmen have a larger trunk muscle CSA and greater strength than age-matched untrained men. Rowing exercise, which includes elements of both aerobic and resistance exercise, exerts favorable effects on skeletal muscle mass and physical function in elderly people.

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ORIGINAL PAPER

Effect of combined resistance and aerobic training on reactive hyperemia in men

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Abstract Reduced response to reactive hyperemia (RH) in the extremities reflects impaired endothelium-dependent vasodilation of the microvasculature. The aims of the present study were to determine whether resistance training and a combination of aerobic and resistance training increase the endothelial vasodilation of the forearm assessed by RH. A total of 39 young men were assigned to either high-intensity resistance training (HIR; six types of exercises, 80% 1RM × 10 repetitions × 3 sets, $n = 14$) or moderate-intensity resistance training (MIR; six types of exercises, 50% 1RM × 16 repetitions × 3 sets, $n = 14$) or a combination of high-intensity resistance training and moderate-intensity endurance training (COMBO; HIR and 60% maximal heart rate × 30 min, $n = 11$) groups. We measured forearm blood flow response to RH before and after 4 months of exercise intervention. All training groups increased maximal strength in all muscle groups tested (all $P < 0.05$). After 4 months of training, the forearm blood flow during RH increased significantly in the MIR and COMBO groups, from 57 ± 4 to 66 ± 7 ml/min per 100 ml tissue and from 59 ± 6 to 74 ± 8 ml/min per 100 ml tissue, respectively (both $P < 0.05$). There was no change in the response to RH in the HIR groups. In conclusion, the findings in this study demonstrate that combined resistance and aerobic training may affect the vasoreactivity response to RH in the forearm, but not resistance training alone.

Keywords Reactive hyperemia · Endothelial function · Blood flow · Resistance training · Exercise · Combined training

Introduction

Reduced response to reactive hyperemia (RH) in the forearm or leg, reflecting impaired endothelium-dependent vasodilation of the microvasculature, is an independent predictor of cardiovascular morbidity [1, 2] or mortality [3]. Recently, it has been reported that daily aerobic exercise augments forearm blood flow response to RH, suggesting improved endothelial function of the microvasculature [4–6]. Therefore, aerobic training is being recommended as an effective way of preventing and improving endothelial dysfunction.

Resistance training has become a popular modality of exercise performed by most populations, and has become an integral component of exercise recommendations endorsed by a number of national health organizations [7, 8]. It is important to determine an effective exercise program incorporating resistance exercises on endothelium-dependent vasodilation in the microvasculature, an independent risk factor for cardiovascular disease [1, 2]. We and others have demonstrated that high- and moderate-intensity resistance training is associated with reduced arterial compliance by using longitudinal or cross-sectional studies [9–11], but not with a change of endothelial function in conduit arteries (carotid or brachium) [12, 13].

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It remains unclear, however, whether the resistance training favorably affects endothelium-dependent vasodilation, in particular, the microvasculature. Furthermore, to gain and maintain cardiorespiratory fitness, muscle strength or healthy cardiovascular function, the importance of combined endurance and resistance exercise has been reported by some papers [10, 14–18], but the effects on endothelial function of the microvasculature evaluated by using RH is not known.

Accordingly, the aims of the present study were to determine whether resistance training and a combination of aerobic and resistance training increase the endothelial function of the forearm assessed by using RH. To investigate in detail the effects of resistance training, a total of 39 young men were randomly assigned to groups for either high-intensity resistance (HIR) or moderate-intensity resistance (MIR) training or a combination of high-intensity resistance training and moderate-intensity endurance (COMBO) training. We measured forearm blood flow response to RH, an index of endothelium-dependent vasodilation in the microvasculature, before and after the 4-month interventional study, and hypothesized that MIR training and combined resistance and aerobic training induce enhancement of the endothelial function of the forearm assessed by RH, if MIR as well as COMBO training have aerobic factors or components, including increased heart rate or blood flow during exercise.

Methods

Subjects

A total of 39 young healthy men 19 to 38 years old were studied. We excluded subjects who had participated in any resistance or endurance training on a regular basis (i.e., >3/week), but included subjects who had taken part in recreational activities. All subjects were normotensive (blood pressure <140/90 mmHg), nonobese (body mass index <30 kg/m^2) and free of overt chronic diseases as assessed by their medical history and a physical examination. Candidates who had smoked in the previous 4 years, who were taking medications or anabolic steroids, or who had significant intima-media thickening, plaque formation and/or other characteristics of atherosclerosis (e.g., ankle-brachial index <0.9) were excluded. All subjects gave their written informed consent to participate, and all procedures were approved by the Institutional Review Board. Subjects were randomly assigned into the HIR group ($n = 14$), the MIR group ($n = 14$) or the COMBO group ($n = 11$). Before the intervention period, there were no significant differences in any of the variables between the groups.

Measurements

Three groups were studied three times: before training, at 2 months and after 4 months of exercise training. To avoid potential diurnal variations, subjects were tested at the same time of day throughout the study period [9, 19]. Before each testing, subjects abstained from caffeine and fasted for at least 4 h; most subjects were studied after an overnight fast. Subjects were studied 20–24 h after their last exercise training session to avoid the acute effects of exercise, but they were still considered to be in their normal (i.e., habitually exercising) physiological state.

Incremental exercise

To demonstrate that participants had been sedentary, we measured the maximal oxygen consumption during incremental cycle ergometer exercise [20]. The oxygen consumption, heart rate and ratings of perceived exertion were measured throughout the protocol.

Strength testing

Maximal muscular strength was assessed before and after resistance training using the following exercises: half squat, bench press, leg extension, leg curls, lateral row and abdominal bend. After ten warm-up repetitions, one-repetition maximum (1RM) values were obtained according to established guidelines. The day-to-day coefficient of variation for 1RM strength in our laboratory is 4 ± 2%.

Body composition

The body composition was determined using the bioelectric impedance method (coefficient of variance 4 ± 2%).

Arterial blood pressure and heart rate at rest

Chronic levels of arterial blood pressure or heart rate at rest were measured with a semiautomated device (Form PWV/ABI, Colin Medical, Komaki, Aichi, Japan) [21]. Recordings were made in triplicate with participants in the supine position.

Forearm blood flow following RH

Forearm blood flow was measured by using a mercury-filled silastic strain-gauge plethysmograph (EC-5R, DE Hokanson Inc.), as previously described [5]. A cuff was placed around the right upper arm of the subject. A strain gauge around the widest part of the forearm on the same side was connected to the plethysmography device and supported above the level of the right atrium. The upper