

## Poor trunk flexibility is associated with arterial stiffening

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**Yamamoto K, Kawano H, Gando Y, Iemitsu M, Murakami H, Sanada K, Tanimoto M, Ohmori Y, Higuchi M, Tabata I, Miyachi M.** Poor trunk flexibility is associated with arterial stiffening. *Am J Physiol Heart Circ Physiol* 297: H1314–H1318, 2009. First published August 7, 2009; doi:10.1152/ajpheart.00061.2009.—Flexibility is one of the components of physical fitness as well as cardiorespiratory fitness and muscular strength and endurance. Flexibility has long been considered a major component in the preventive treatment of musculo-tendinous strains. The present study investigated a new aspect of flexibility. Using a cross-sectional study design, we tested the hypothesis that a less flexible body would have arterial stiffening. A total of 526 adults, 20 to 39 yr of age (young), 40 to 59 yr of age (middle-aged), and 60 to 83 yr of age (older), participated in this study. Subjects in each age category were divided into either poor- or high-flexibility groups on the basis of a sit-and-reach test. Arterial stiffness was assessed by brachial-ankle pulse wave velocity (baPWV). Two-way ANOVA indicated a significant interaction between age and flexibility in determining baPWV ( $P < 0.01$ ). In middle-aged and older subjects, baPWV was higher in poor-flexibility than in high-flexibility groups (middle-aged,  $1,260 \pm 141$  vs.  $1,200 \pm 124$  cm/s,  $P < 0.01$ ; and older,  $1,485 \pm 224$  vs.  $1,384 \pm 199$  cm/s,  $P < 0.01$ ). In young subjects, there was no significant difference between the two flexibility groups. A stepwise multiple-regression analysis ( $n = 316$ ) revealed that among the components of fitness (cardiorespiratory fitness, muscular strength, and flexibility) and age, all components and age were independent correlates of baPWV. These findings suggest that flexibility may be a predictor of arterial stiffening, independent of other components of fitness.

arteriosclerosis; blood pressure; prevention; fitness

ARTERIAL STIFFNESS has been identified as an independent risk factor for mortality and cardiovascular disorders (2, 16, 17, 22). Higher levels of physical fitness, especially cardiorespiratory fitness, appear to delay an age-related arterial stiffening (4, 25). Although flexibility is one of the components of physical fitness, the relationship between flexibility and arterial stiffness remains unclear.

Structurally, arterial stiffness is determined by the intrinsic elastic properties of smooth muscle and/or connective tissue (e.g., elastin-collagen composition) in the artery (19). Flexibility is also determined by skeletal muscle and/or connective tissue in the tendon, ligaments, and fascia (1). Age-related alterations in the muscles or connective tissues in the arteries may correspond to similar age-related alterations in the whole body (8). Accordingly, we hypothesized that a less flexible body would indicate arterial stiffening. To test our hypothesis,

we examined the relationship between flexibility and arterial stiffness in three age categories using a cross-sectional study.

### METHODS

**Subjects.** A total of 526 adults (178 males and 348 females), 20 to 39 yr of age (young), 40 to 59 yr of age (middle-aged), and 60 to 83 yr of age (older), participated in this study. All subjects were non-obese (body mass index  $< 30$ ) and free of overt chronic diseases as assessed by medical history, physical examination, and complete blood chemistry and hematological evaluation (e.g., plasma glucose concentration  $< 126$  mg/dl, and total cholesterol  $< 240$  mg/dl). Candidates who smoked in the past 4 yr, were taking medications, or had characteristics of peripheral arterial disease [ankle-brachial index (ABI)  $< 0.9$ ] were excluded. The purpose, procedures, and risks of the study were explained to each participant before inclusion, and all subjects 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. All subjects were recruited to the same site (National Institute of Health and Nutrition). The study was performed in accordance with the guidelines of the Declaration of Helsinki.

To assess the effects of flexibility on arterial stiffness, the subjects in each age category were divided into either poor- or high-flexibility groups on the basis of the mean value of a sit-and-reach test every 10 yr of age in each sex. We attempted to isolate the influence of flexibility as much as possible. To do so, poor- and high-flexibility groups were carefully matched for age, height, weight, and metabolic risk factors.

Before they were tested, the subjects abstained from caffeine and fasted for at least 4 h (a 12-h overnight fast was used to determine arterial stiffness and blood pressure). Subjects also abstained from heavy exercise for at least 24 h to avoid the immediate (acute) effects of exercise. All subjects were tested between 9:00 AM and 12:00 AM.

**Arterial stiffness.** After 10 min of quiet rest in the supine position, subjects were studied in the supine position. Bilateral brachial and ankle blood pressures were simultaneously measured with a vascular testing device (form PWV/ABI; Omron Colin, Kyoto, Japan). Bilateral brachial and ankle arterial pressure waveforms were stored for 10 s by extremity cuffs connected to a plethysmographic sensor and an oscillometric pressure sensor wrapped on both arms and ankles. The brachial-ankle pulse wave velocity (baPWV) was calculated from the distance between two arterial recording sites divided by the transit time (14, 21, 28). The value of baPWV mainly reflects stiffness in the central arteries (21, 28), because baPWV correlates well with the aortic PWV using a catheter tip with a pressure manometer (28). The mean value of right and left baPWV was obtained for analysis. The standard deviation of the differences for interobserver reproducibility was 51 cm/s in our laboratory (3, 28).

In 309 (107 males and 202 females) of the pooled population, brachial, ankle, carotid, and femoral arterial pulse waves were simultaneously measured with the vascular testing device (form PWV/ABI; Omron Colin) for assessing aortic PWV and femoral-ankle PWV (faPWV). Carotid and femoral arterial pressure waveforms were

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stored for 30 s by applanation tonometry sensors attached on the left common carotid and left common femoral arteries. Aortic PWV was calculated from the distance between the carotid and femoral artery sites divided by the transit time. The standard deviation of the differences for interobserver reproducibility was 62 cm/s in our laboratory. The faPWV was calculated from the distance between the femoral and ankle artery sites divided by the transit time. The standard deviation of the differences for interobserver reproducibility was 44 cm/s in our laboratory (3, 28).

**Flexibility.** Flexibility was measured by a sit-and-reach test using a digital flexibility testing device (T.K.K.5112; Takeikiki, Tokyo, Japan) after some stretching. The device displays the distance which the device moved. Subjects sat on the floor, attaching their hip, back, and occipital region of the head to a wall, with legs held straight by a tester. They put both hands on the device, with arms held straight. In the position, zero point of the device was set. They were then asked to bend forward slowly and reach as far forward as possible. The best of two trials was recorded (24). The standard deviation of the differences for interobserver reproducibility was 2.3 cm in our laboratory.

**Cardiovascular fitness and muscular strength.** Physical fitness is mainly composed of cardiorespiratory fitness, muscular strength and endurance, and flexibility. To examine the relationship among flexibility, cardiorespiratory fitness, and muscular strength in determining arterial stiffness, we measured peak oxygen uptake as an indicator of cardiorespiratory fitness and leg extension power as an indicator of muscular strength. The leg extension power was determined using a dynamometer (Anaero Press 3500; Combi Wellness, Tokyo, Japan) in the sitting position. The subjects were advised to vigorously extend their legs. Five trials were performed at 15-s intervals, and the average of the two highest recorded power outputs (in W) was taken as the definitive measurement (29). The peak oxygen uptake was determined by incremental cycle ergometer exercise (27). The highest value of oxygen uptake during the exercise test was designated as peak oxygen uptake. Because the test requires an incremental cycle exercise to exhaustion, subjects could determine their participation in the test. Three hundred sixteen (95 males and 221 females) subjects of the pooled population participated in the test.

**Statistical analysis.** All data are presented as means  $\pm$  SE. The data were analyzed by two-way ANOVA (age  $\times$  flexibility) and analysis of covariance (ANCOVA) that included sex as a covariate. In the case

of a significant *F* value, a post hoc test with Scheffé's method identified significant differences among mean values. Univariate regression and correlation analyses were used to analyze the relationships between variables of interest. Stepwise multiple regression analysis was used to determine the influences of age, sit-and-reach, peak oxygen uptake, and leg power on baPWV. Differences were considered significant when *P* < 0.05.

## RESULTS

Table 1 shows the subject characteristics. In each age category, age, height, weight, and all metabolic risk factors did not differ between high-flexibility and poor-flexibility groups. In middle-aged and older subjects, the systolic blood pressure was higher in poor-flexibility than in high-flexibility groups. In middle-aged subjects, the pulse pressure was higher in the poor-flexibility than in the high-flexibility groups.

Table 2 shows the effects of age and flexibility on baPWV, aortic PWV, and faPWV. In baPWV, two-way ANOVA indicated a significant interaction between age and flexibility in determining baPWV (*P* < 0.05). Within both flexibility groups, baPWV was higher in middle-aged and older subjects compared with young subjects. The baPWV was also higher in older subjects compared with middle-aged subjects. Most importantly, in middle-aged and older subjects, baPWV was higher in the poor-flexibility than in the high-flexibility groups. The differences remained significant after normalizing baPWV for sex when analyzed by ANCOVA. In the young subjects, there was no significant difference between the two flexibility groups. In aortic PWV, two-way ANOVA indicated a significant interaction (*P* < 0.05). In middle-aged and older subjects, aortic PWV was higher in the poor-flexibility than in the high-flexibility groups. The differences remained significant after normalizing aortic PWV for sex when analyzed by ANCOVA. In faPWV, there were no significant differences between the two flexibility groups in each age category.

Figure 1 shows the relationships between sit-and-reach and baPWV (*A*) or aortic PWV (*B*) in each age category. The

Table 1. Characteristics of the subjects

	Young		Middle-Aged		Older	
	High	Poor	High	Poor	High	Poor
<i>N</i>	98	92	104	100	71	61
Age, yr	26 $\pm$ 1	26 $\pm$ 1	49 $\pm$ 1*	49 $\pm$ 1*	67 $\pm$ 1*†	67 $\pm$ 1*†
Height, cm	169 $\pm$ 1	168 $\pm$ 1	161 $\pm$ 1*	159 $\pm$ 1*	156 $\pm$ 1*†	155 $\pm$ 1*†
Weight, kg	60 $\pm$ 1	61 $\pm$ 1	61 $\pm$ 1	60 $\pm$ 1	55 $\pm$ 1*†	54 $\pm$ 1*†
SBP, mmHg	110 $\pm$ 1	109 $\pm$ 1	116 $\pm$ 1*	121 $\pm$ 1*‡	124 $\pm$ 2*†	129 $\pm$ 2*‡
DBP, mmHg	62 $\pm$ 1	62 $\pm$ 1	70 $\pm$ 1*	72 $\pm$ 1*	72 $\pm$ 1*	74 $\pm$ 1*
PP, mmHg	48 $\pm$ 1	48 $\pm$ 1	45 $\pm$ 1	48 $\pm$ 1‡	52 $\pm$ 1*†	55 $\pm$ 2*†
Hypertension, %	0	0	8	11	20*†	30*†
Heart rate, beats/min	57 $\pm$ 1	56 $\pm$ 1	61 $\pm$ 1*	62 $\pm$ 1*	59 $\pm$ 1	57 $\pm$ 1
Total cholesterol, mmol/l	4.48 $\pm$ 0.07	4.52 $\pm$ 0.07	5.13 $\pm$ 0.05*	5.19 $\pm$ 0.05*	5.35 $\pm$ 0.06*†	5.27 $\pm$ 0.07*
HDL cholesterol, mmol/l	1.61 $\pm$ 0.04	1.57 $\pm$ 0.03	1.72 $\pm$ 0.04	1.71 $\pm$ 0.04*	1.68 $\pm$ 0.04	1.68 $\pm$ 0.05
Plasma glucose, mmol/l	4.90 $\pm$ 0.04	4.88 $\pm$ 0.04	5.14 $\pm$ 0.05*	5.21 $\pm$ 0.04*	5.22 $\pm$ 0.05*	5.24 $\pm$ 0.08*
Sit-and-reach, cm	47 $\pm$ 1	32 $\pm$ 1‡	46 $\pm$ 1	31 $\pm$ 1‡	41 $\pm$ 1*†	26 $\pm$ 1*‡
Leg extension power, W/kg	23 $\pm$ 1	22 $\pm$ 1	18 $\pm$ 1*	17 $\pm$ 1*	14 $\pm$ 1*†	13 $\pm$ 1*†
<i>N</i>	62	62	82	57	27	26
Peak oxygen uptake, ml·min <sup>-1</sup> ·kg <sup>-1</sup>	37 $\pm$ 1	36 $\pm$ 1	32 $\pm$ 1*	29 $\pm$ 1*‡	28 $\pm$ 1*†	25 $\pm$ 1*†

Values are means  $\pm$  SE; *N*, number of subjects; high and poor, high-flexibility and poor-flexibility groups, respectively; SBP and DBP, brachial systolic blood pressure and diastolic blood pressure, respectively; PP, brachial pulse pressure. Hypertension  $\geq$  140/90 mmHg. The criterion for division between 2 groups was the mean value of the sit-and-reach test every 10 yr of age in each sex in this population. \**P* < 0.05 vs. young within same flexibility group; †*P* < 0.05 vs. middle-aged within same flexibility group; ‡*P* < 0.05 vs. high-flexibility within same age category.

Table 2. Arterial stiffness in high- or poor-flexibility groups

	Young		Middle-Aged		Older	
	High	Poor	High	Poor	High	Poor
<i>N</i>	98	92	104	100	71	61
baPWV, cm/s	1,080 ± 12	1,085 ± 11	1,200 ± 12*	1,260 ± 14*‡	1,384 ± 24*†	1,485 ± 29*†‡
<i>N</i>	38	37	82	84	37	31
Aortic PWV, cm/s	732 ± 18	731 ± 17	788 ± 9*	825 ± 12*‡	902 ± 24*†	1,004 ± 29*†‡
faPWV, cm/s	871 ± 15	849 ± 14	916 ± 10*	970 ± 26*	984 ± 14*†	1,016 ± 23*

Values are means ± SE; *N*, number of subjects. baPWV, brachial-ankle pulse wave velocity (PWV); aortic PWV, carotid-femoral PWV; faPWV, femoral-ankle PWV. The criterion for division between 2 groups was the mean value of the sit-and-reach test every 10 yr of age in this population. \* $P < 0.05$  vs. young within same flexibility group; † $P < 0.05$  vs. middle-aged within same flexibility group; ‡ $P < 0.05$  vs. high-flexibility within same age category.

baPWV and aortic PWV correlated with sit-and-reach in middle-aged (Fig. 1, *middle*) and older (Fig. 1, *right*) subjects. In young subjects (Fig. 1, *left*), there were no relationships. The slope of the relationship was steeper in older subjects than in middle-aged subjects in both baPWV and aortic PWV ( $P < 0.001$ ).

A univariate regression analysis indicated that sit-and-reach positively correlated with peak oxygen uptake ( $r = 0.20$ ,  $P < 0.001$ ) and leg power ( $r = 0.13$ ,  $P < 0.05$ ). The analysis also indicated that baPWV negatively correlated with peak oxygen uptake ( $r = -0.37$ ,  $P < 0.001$ ) and leg power ( $r = -0.32$ ,  $P < 0.001$ ). A stepwise multiple-regression analysis revealed that among the components of fitness and age, sit-and-reach ( $\beta = -0.14$ ), peak oxygen uptake ( $\beta = -0.12$ ), leg power ( $\beta = 0.17$ ), and age ( $\beta = 0.61$ ) were independent correlates of baPWV.

## DISCUSSION

The key new findings of the present study are as follows. First, in middle-aged and older subjects, arterial stiffness de-

teriorated in the poor-flexibility groups compared with the high-flexibility groups. Second, a negative relationship between flexibility and arterial stiffness was observed in middle-aged and older subjects, but there were no relationships in young subjects. These results support our hypothesis that a less flexible body indicates arterial stiffening, especially in middle-aged and older adults. Furthermore, age-related arterial stiffening was greater (~30% in baPWV) in the poor-flexibility than in the high-flexibility groups, which suggests that poor flexibility is associated with greater age-related arterial stiffening.

In general, because habitual exercise includes flexibility exercise (e.g., stretching during warming up or cooling down), an active person may tend to be more flexible than an inactive one (11). In fact, a positive relationship between cardiorespiratory fitness and flexibility was observed in the present study. It is well known that cardiorespiratory fitness was inversely related to arterial stiffness (25). The present study also showed that both peak oxygen uptake and leg power are inversely related to baPWV. Stepwise multiple-regression analysis re-

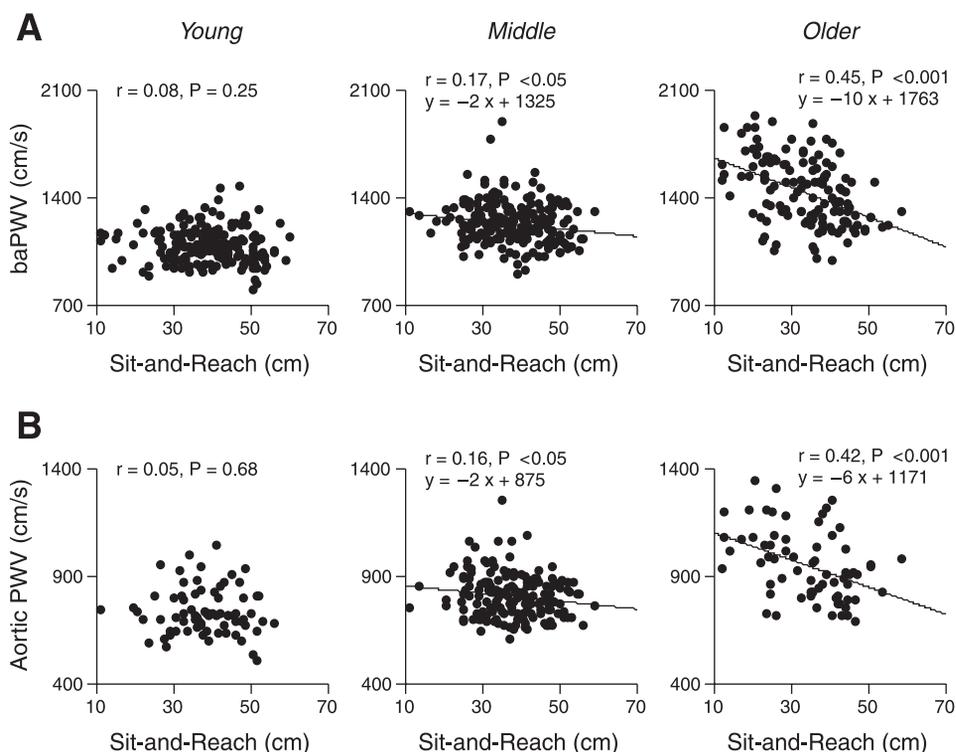


Fig. 1. Relationships between sit-and-reach and brachial-ankle pulse wave velocity (baPWV; *A*) or aortic PWV (*B*) in each age category. The baPWV and aortic PWV correlated with sit-and-reach in middle-aged (*middle*) and older (*right*) subjects. In both baPWV and aortic PWV, slope of the relationship was steeper in older subjects than in middle-aged subjects ( $P < 0.001$ ).

vealed that among the components of fitness and age, sit-and-reach was an independent correlate of baPWV. These findings statistically support the idea that flexibility is identified as a determinant or predictor of arterial stiffness, independent of other components of fitness. On the other hand, the peak oxygen uptake was also an independent correlate of baPWV. This result may indicate that subjects who have low cardiorespiratory fitness have higher arterial stiffness than high cardiorespiratory fitness subjects in high-flexibility groups. The same might apply for physical activity. The interaction among flexibility and other components of fitness or physical activity in determining the arterial stiffness awaits further studies.

Recently, Cortez-Cooper et al. (7) examined the effects of strength training on central arterial compliance in middle-aged and older adults. In this previous study, a stretching exercise group was included as a control group. An unexpected finding of the study was that a stretching program significantly increased carotid arterial compliance. Together with our results, these findings suggest a possibility that improving flexibility induced by the stretching exercise may be capable of modifying age-related arterial stiffening in middle-aged and older adults.

Ehlers-Danlos syndrome is a rare connective tissue disorder inherited as an autosomal-dominant trait. As a result, the patients are pathologically hyperflexible. A previous study showed abnormally low values of aortic PWV in the ecchymotic Ehlers-Danlos syndrome (10). Furthermore, Boutouyrie et al. (5) reported that carotid distensibility was 27% higher in the vascular type Ehlers-Danlos syndrome than in control subjects. Thus patients with Ehlers-Danlos syndrome are less likely to have stiff arteries. In contrast, people with spinal cord injury seem to be immobile subjects, indicating the loss of ligamentous laxity. A recent study showed that the aortic PWV among people with spinal cord injuries was higher than that in control subjects (18). These pathological observations are in line with the present results.

We can only speculate on the mechanisms responsible for the greater age-related arterial stiffening in the poor-flexibility groups. First, both arterial stiffness and flexibility may be structurally determined by similar compositions such as the muscles or connective tissues (e.g., elastin-collagen composition) (19). Thus age-related alterations in arterial stiffness may correspond to age-related alterations in flexibility within the same individual. Second, arterial stiffness is functionally determined by the vascular tone of the artery (19). Vascular tone is partially regulated by sympathetic nerve activity. Stretching of skeletal muscle causes an increase in sympathetic nerve activity via the central nervous system (26). Repetitive stimulation of transient sympathoexcitation induced by habitual stretching exercises, which improve flexibility, may chronically reduce resting sympathetic nerve activity. This reduction in sympathetic nerve activity may result in a decrease in arterial stiffness. On the other hand, the higher sympathetic nerve activity elevates blood pressure. In middle-aged and older subjects, systolic blood pressure in the poor-flexibility group was higher than in the high-flexibility group (Table 1). Elevated blood pressure can increase arterial stiffness (19). In this regard, heart rate (HR) appears to be low for young and older subjects, suggesting a well-conditioned population. If sympathetic nerve activity in poor-flexibility groups is higher than that in high-flexibility groups, then HR might be higher in

poor-flexibility groups. Although sympathetic nerve activity increases with age, HR appears unchanged because of age-related decrease in intrinsic HR (6, 15). Further experimental studies are needed to verify the proposed mechanisms related to the present findings.

Our findings have potentially important clinical implications. Trunk flexibility can be easily evaluated over all ages and in any practical fields. Thus a measurement of flexibility as a physical fitness might contribute to assist in the prevention of age-related arterial stiffening. Stretching is widely recommended for injury prevention despite the limited evidence (9). In addition to the recommendation, we believe that flexibility exercise such as stretching, yoga, and pilates would be integrated as a new recommendation into the known cardiovascular benefit of regular exercise. However, although the present results are the first to provide evidence demonstrating that poor flexibility is associated with greater age-related arterial stiffening, the present cross-sectional study provided only associations among age, flexibility, and arterial stiffness. An intervention study is also needed to determine the cause-and-effect relationship between flexibility and arterial stiffness.

We used baPWV for an estimation of arterial stiffness. A major advantage of baPWV is its simple way of measurement by only wrapping the four extremities with blood pressure cuffs. This technique does not need the refined technique of applanation tonometry that is required for the measurements of aortic PWV. Although the value of baPWV mainly reflects stiffness in the central arteries (21, 28), baPWV includes stiffness from the brachial part, the ascending and descending aorta, and the abdominal aorta and leg part. When compared with central elastic arteries, peripheral arteries are generally considered to be of less clinical significance (20). Aortic PWV has been directly linked with cardiovascular mortality and morbidity (2, 16, 17, 22). In the present study, the same results as the baPWV were obtained by the use of the aortic PWV (Table 2, and Fig. 1). In contrast, faPWV did not differ between the poor-flexibility and high-flexibility groups (Table 2). Therefore, we believe that baPWV provides qualitatively similar information as that derived from aortic PWV in this cross-sectional study and that the faPWV may be less sensitive to physical fitness or daily activity compared with the baPWV and aortic PWV (13, 23).

The present study has several limitations. First, we used the sit-and-reach test as an indicator of flexibility. The sit-and-reach test may be differentially influenced by arm and leg length or sex. In the present study, we set an individual zero point for each subject (see flexibility in METHODS for details). Thus the effects of arm and leg length were few. Furthermore, the differences between the two flexibility groups remained significant after normalizing baPWV and aortic PWV for sex when analyzed by ANCOVA. Although the sit-and-reach test has been commonly used to assess flexibility as health-related fitness, the test reflects trunk flexibility. We did not examine the flexibility of other regions such as neck, shoulder, and/or lower extremity. Further investigations are required to improve our understanding of the relationship between flexibility and arterial stiffness. Second, subjects in the present study included premenopausal women. The elastic properties of central arteries fluctuate with the phases of the menstrual cycle (12). However, we did not monitor the menstrual phase in the present study. Thus, if premenopausal women in this popula-

tion are tested during the early follicular phase, the relationship between flexibility and arterial stiffness could be analyzed more accurately.

In conclusion, the present results indicate that poor flexibility is associated with greater age-related arterial stiffening. The association was independent of cardiorespiratory fitness and muscular strength. These findings suggest the possibility that flexibility may be a predictor of arterial stiffening, independent of other components of fitness.

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