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ORIGINAL ARTICLE

Vigorous physical activity and carotid distensibility in young and mid-aged adults

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Although physical activity (PA) improves arterial distensibility, it is unclear which type of activity is most beneficial. We aimed to examine the association of different types of PA with carotid distensibility (CD) and the mechanisms involved. Data included 4503 Australians and Finns aged 26–45 years. Physical activity was measured by pedometers and was self-reported. CD was measured using ultrasound. Other measurements included resting heart rate (RHR), cardiorespiratory fitness (CRF), blood pressure, biomarkers and anthropometry. Steps/day were correlated with RHR (Australian men $r=-0.10$, women $r=-0.14$; Finnish men $r=-0.15$, women $r=-0.11$; $P<0.01$), CRF and biochemical markers, but not with CD. Self-reported vigorous leisure-time activity was more strongly correlated with RHR (Australian men $r=-0.23$, women $r=-0.19$; Finnish men $r=-0.20$, women $r=-0.13$; $P<0.001$) and CRF, and was correlated with CD (Australian men $r=0.07$; Finnish men $r=0.07$, women $r=0.08$; $P<0.05$). This relationship of vigorous leisure-time activity with CD was mediated by RHR independently of potential confounders. In summary, vigorous leisure-time PA but not total or less intensive PA was associated with arterial distensibility in young to mid-aged adults. Promotion of vigorous PA is therefore recommended among this population. RHR was a key intermediary factor explaining the relationship between vigorous PA and arterial distensibility.
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INTRODUCTION

Large arteries such as the carotid and aorta stiffen with age even in healthy individuals.[1] Decreased distensibility (or increased stiffness) of large arteries can independently predict cardiovascular events and all-cause mortality,[2–4] and is one of the most important contributors to the increased cardiovascular risk with aging.[5] Thus, any lifestyle factors that can delay this process hold promise for reducing age-associated cardiovascular disease.

Intervention studies have reported light-to-moderate physical activity (PA) to increase arterial distensibility among older adults.[6,7] However, it is unclear whether these results can be extrapolated to younger adults and there is limited information on the type of PA that exerts the most beneficial effect on arterial distensibility. Current guidelines[8] reflect the thinking that reduction in cardiovascular risks can be achieved by participating in either vigorous PA or light-to-moderate PA (with longer time required). Walking, assessed by questionnaire or by motion sensors such as pedometers or accelerometers, has been shown to have a range of cardio-metabolic benefits[9–11] but its association with arterial distensibility is less clear. Recent evidence suggests that vigorous PA may provide cardioprotective benefits that are beyond those achieved through light-to-moderate PA[12,13] but associations of objectively measured steps/day with arterial distensibility have not been previously investigated. Clarifying this matter is important for informing advice on PA to promote cardiovascular health.

In previously published work, we found resting heart rate (RHR) to be a key intermediary factor in the positive relationship between cardiorespiratory fitness (CRF) and carotid distensibility (CD).[14] In this study, using data on 4503 young to mid-aged adults from two large population-based cohorts in Australia and Finland, we examined the relationship of different types of PA, including pedometer measured steps/day, with CD and, for comparison, other cardiovascular risk factors. We sought to determine whether the association varied by type of PA and aimed to investigate whether RHR is also a key intermediary factor in this relationship.

MATERIALS AND METHODS

This study included data from two large population-based prospective cohort studies in Australia and Finland. Each study was approved by local ethics committees. All participants provided written informed consent.

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Australia: the Childhood Determinants of Adult Health study

Study population. The Childhood Determinants of Adult Health (CDAH) study collected baseline data in 1985 on a nationally-representative sample of 8498 Australian schoolchildren aged 7–15 years.[15] In this study, we included 2328 non-pregnant participants aged 26–36 years (49.4% male) who attended one of 34 study clinics across Australia at follow-up during May 2004–May 2006.[16] Of these participants, 1787 (76.8%) had their arterial distensibility measured.

Physical activity. Daily steps were recorded using Yamax Digiwalker SW-200 pedometers for 7 days.[9] Average steps per day was calculated for participants wearing pedometers at least 8 h per day for at least 4 days,[17] consistent with other studies.[18] PA in previous week was self-reported using the International Physical Activity Questionnaire.[19] Minutes per week spent on work-related, domestic and recreational PA at moderate and vigorous intensity was recorded together with time spent in active transport (classified as moderate intensity). These were summed to obtain total minutes of moderate-to-vigorous PA, and moderate and vigorous activities were weighted—by assigning metabolic equivalent of task (MET) values of four and eight respectively—to obtain total PA energy expenditure.

Arterial distensibility and blood pressure. End-systolic and end-diastolic diameters, and intima-media thickness of the left common carotid artery were measured using a portable Acuson Cypress (Siemens Medical Solutions USA Inc., Mountainview, CA, USA) platform with a 7.0 MHz linear-array transducer by a single technician, following a standardized protocol.[16,20] Before its inclusion in the CDAH study, the ultrasound measures derived from this portable Acuson Cypress were validated against those from a routinely-used clinic-based ultrasound machine like that used in the Cardiovascular Risk in Young Finns study (Acuson Sequoia 512, Siemens Medical Solutions USA Inc.).[21] Brachial systolic blood pressure (SBP) and diastolic blood pressure (DBP) were measured during the ultrasound with a mean of two readings used in this study.[16] The inverse of stiffness (CD) was calculated as follows:[14,16]

$$CD = ([D_{sbp} - D_{dbp}]/D_{dbp})/(SBP - DBP)$$

where D_{sbp} and D_{dbp} are the end-systolic and end-diastolic diameters.

Other cardiovascular risk factors. Body mass index (BMI) was calculated as weight(kg)/height(m^2). Mean arterial pressure (MAP) was calculated as $MAP = \frac{1}{3}SBP + \frac{2}{3}DBP$. RHR was measured while sitting after at least a 5-min rest using an Omron HEM907 Blood Pressure Monitor (Omron Corporation, Kyoto, Japan). Concentrations of high-density lipoprotein cholesterol (HDL-C), triglycerides, insulin and glucose were measured in 12-h overnight fasting blood samples.[16] Low-density lipoprotein cholesterol (LDL-C) concentration was calculated using the Friedewald formula.[22] Because the absolute workload achieved is partly a function of muscle mass,[23] physical working capacity measured by a bicycle ergometer[24] at a heart rate of 170 beats per minute was adjusted for lean body mass to create an index of CRF that is uncorrelated with lean body mass. This was previously described elsewhere.[14] The first principal component[25] of five measures of strength (left and right grip, shoulder push and pull and leg strength) was measured by appropriate dynamometers (Smedley's Dynamometer, TTM, Tokyo, Japan) and adjusted for body weight to create an index of muscular strength that is uncorrelated with weight.[14] Data on socio-economic status, smoking and alcohol consumption were obtained by questionnaire.[16]

Finland: the Cardiovascular risk in Young Finns study

Study population. The Young Finns study collected baseline data in 1980 on 3596 Finnish children and adolescents aged 3–18 years.[26] In this study, we included 2175 non-pregnant participants aged 30–45 years (45.8% male) who attended a clinic in Finland during the follow-up in 2007. Of these participants, 2169 (99.7%) had their arterial distensibility measured.

Physical activity. In 2007, participants of Young Finns study wore Omron Walking Style One (HJ-152 R-E) pedometers (Kyoto, Japan) to record daily steps for 7 days.[27] Average steps per day was calculated for participants wearing pedometers at least 8 h per day for 4 days, consistent with other studies including CDAH.[9,18] Leisure-time and transport PA were obtained by questionnaire, and a value of MET.hour per week was calculated based on these two subdomains of PA for Young Finns participants, which has been described elsewhere.[28] Vigorous leisure-time PA per usual week was reported by choosing one of the six response categories: 'none', 'approximately 30 min', '1 h', '2–3 h', '4–6 h' and '7 h or more'.

Arterial distensibility and blood pressure. Using a similar standardized protocol as in CDAH,[16,20] end-systolic and end-diastolic diameters and intima-media thickness were measured from the left common carotid artery by Sequoia 512 ultrasound mainframes (Acuson) with 13.0 MHz linear-array transducers, together with concomitant brachial blood pressure. CD was calculated using the same formula as in CDAH.[20]

Other cardiovascular risk factors. Using similar standardized protocols and formulas as in CDAH, BMI and MAP were calculated, RHR was measured while sitting after at least a 5-min rest, 12-h overnight fasting concentrations of HDL-C, triglycerides, insulin and blood glucose were measured,[20] LDL-C concentration was calculated using the Friedewald formula,[22] and data on socio-economic status, smoking and alcohol consumption were obtained by a questionnaire.[29] CRF was objectively estimated in a random subsample of 538 participants (47.8% male) by a bicycle ergometer using hypothetical maximal workload sustainable for 6 min measured on the basis of age, sex, height and weight, following a previously reported protocol.[30] Because this measure of CRF was estimated based on height and weight, we did not further adjust for lean body mass.

Statistical analyses

For analyses, right-skewed outcome data (CD and other risk factors) were transformed before estimation of their means or linear regression. The regression estimates reported are in the original units of the outcomes for one unit increase in the study factor.[31] In both cohorts, vigorous PA was defined as those that required hard physical effort and made the participants breathe much harder than normal. Participants of each sex in each sample were classified as spending no time, <2 h per week, 2–3 h per week or >3 h per week in vigorous leisure-time PA. For estimation of trend, these ordered levels were graded by consecutive integer scores. For estimation of relative risk, low arterial distensibility was defined by having CD$<$10th percentile specific for each sample, each sex and each year of age. Based on the concept of 'vascular age' for intima-media thickness,[32] we used linear regression to estimate sample- and sex-specific rates of decreasing CD per year of age after adjusting for BMI, PA, socio-economic status, smoking and alcohol consumption. We then calculated the mean difference in 'vascular age' of participants who spent at least 1 h per week in vigorous PA, as in guidelines,[8] compared with that of those who did not by dividing the difference in CD by the rate of decreasing CD per year of age. The percentage by which RHR explained the relationship of PA with CD was calculated by subtracting the direct effect (adjusting for RHR and age) from the total effect (adjusting for age only), and then dividing by the total effect. The percentage was set at 100% if adjusting for RHR reversed the sign of the association. Because of similar results in the two cohorts, we reported pooled data analyses in the tables for ease of interpretation. Cohort-specific results are shown as supplementary content.

RESULTS

Characteristics of participants in the two samples are shown in Table 1. On average, the Young Finns participants were 6 years older than the CDAH participants. Other than having lower RHR, the men in each sample had lower CD and greater BMI, MAP, insulin, glucose, LDL-C and triglycerides, and lower HDL-C, than the women (all $P<0.001$). The risk factor profile of the Young Finns reflected their slightly older age. The pooled data reflected average values of the CDAH and Young Finns samples and were consistent with the participant characteristics in each sample.

CRF was positively correlated with steps/day (CDAH men $r=0.15$, women $r=0.21$; Young Finns men $r=0.33$, women $r=0.25$; all $P<0.001$), and was more strongly correlated with self-reported

Table 1 Characteristics of participants in the two samples

	Men	*Women*
	Mean (s.d.)	*Mean (s.d.)*
CDAH (n = 2328)[a]	49% (1150)	51% (1178)
Age (year)	31.6 (2.6)	31.3 (2.6)
Body mass index (kg m^{-2})	25.9 (3.9)	23.9 (4.2)
Average steps per day	8819 (3426)	8575 (2932)
Total active hours per week	11.3 (8.7)	10.8 (7.9)
Total physical activity (MET.hour per week)	52.6 (44.1)	42.2 (33.3)
Vigorous physical activity		
Any vigorous physical activity[a]	71% (703)	49% (536)
Average hours per week[b]	3.37 (3.41)	2.23 (2.32)
Any vigorous work-related activity[a]	40% (393)	16% (176)
Average hours per week[b]	3.40 (3.39)	2.32 (2.91)
Any vigorous domestic activity[a]	40% (394)	22% (242)
Average hours per week[b]	1.93 (1.83)	1.67 (1.58)
Any vigorous leisure-time activity[a]	49% (479)	40% (436)
Average hours per week[b]	2.13 (2.13)	1.83 (1.66)
Carotid distensibility (%/10mm Hg)	1.94 (0.64)	2.35 (0.79)
Heart rate at rest (bpm)	68.3 (9.9)	73.2 (9.7)
Systolic pressure (mm Hg)	124.6 (10.7)	110.5 (10.1)
Diastolic pressure (mm Hg)	74.5 (8.9)	69.8 (8.6)
Insulin (mU l^{-1})	6.33 (4.0)	5.96 (3.35)
Glucose (mmol l^{-1})	5.14 (0.42)	4.84 (0.40)
HDL-cholesterol (mmol l^{-1})	1.26 (0.25)	1.51 (0.33)
LDL-cholesterol (mmol l^{-1})	3.04 (0.84)	2.74 (0.74)
Triglycerides (mmol l^{-1})	1.03 (0.65)	0.81 (0.42)
Young Finns (*n* = 2175)[a]	46% (996)	54% (1179)
Age (year)	37.6 (5.1)	37.8 (4.9)
Body mass index (kg m^{-2})	26.1 (4.0)	24.5 (4.3)
Average steps per day	6729 (2732)	7509 (2811)
Leisure-time, commuting activity (MET.hour per week)	9.9 (19.2)	12.1 (17.9)
Any vigorous leisure-time activity[a]	67% (667)	77% (895)
Carotid distensibility (%/10 mm Hg)	1.71 (0.62)	1.97 (0.72)
Heart rate at rest (bpm)	66.7 (9.9)	68.9 (9.2)
Systolic pressure (mm Hg)	125.2 (12.8)	115.2 (13.5)
Diastolic pressure (mm Hg)	78.8 (10.9)	73.0 (10.9)
Insulin (mU l^{-1})	7.54 (6.24)	7.00 (5.69)
Glucose (mmol l^{-1})	5.38 (0.54)	5.08 (0.51)
HDL-cholesterol (mmol l^{-1})	1.18 (0.28)	1.41 (0.32)
LDL-cholesterol (mmol l^{-1})	3.22 (0.82)	2.89 (0.72)
Triglycerides (mmol l^{-1})	1.33 (0.77)	1.01 (0.47)
Pooled data (*n* = 4503)[a]	48% (2146)	52% (2375)
Age (year)	35.1 (5.0)	35.0 (5.1)
Body mass index (kg m^{-2})	26.0 (3.9)	24.1 (4.2)
Average steps per day	7788 (3266)	7982 (2933)
Any vigorous leisure-time activity[a]	53% (1146)	56% (1331)
Carotid distensibility (%/10mm Hg)	1.82 (0.64)	2.15 (0.78)
Heart rate at rest (bpm)	67.6 (9.9)	71.2 (9.8)
Systolic pressure (mm Hg)	124.9 (11.7)	112.4 (11.9)
Diastolic pressure (mm Hg)	76.3 (10.1)	71.0 (10.0)
Insulin (mU l^{-1})	6.93 (5.09)	6.47 (4.59)
Glucose (mmol l^{-1})	5.25 (0.51)	4.96 (0.53)
HDL-cholesterol (mmol l^{-1})	1.22 (0.27)	1.46 (0.33)
LDL-cholesterol (mmol l^{-1})	3.13 (0.83)	2.82 (0.74)
Triglycerides (mmol l^{-1})	1.18 (0.74)	0.92 (0.48)

Abbreviations: CDAH, the Childhood Determinants of Adult Health study; HDL, high-density lipoprotein; LDL, low-density lipoprotein; MET, metabolic equivalent of task; Young Finns, the Cardiovascular Risk in Young Finns study.
[a]Data are percentage (number).
[b]Data are reported only for participants who reported some vigorous physical activity of the corresponding subdomain.

vigorous leisure-time PA (CDAH men $r = 0.36$ women $r = 0.35$, Young Finns men $r = 0.41$ women $r = 0.40$, all $P < 0.001$).

Table 2 shows Spearman correlations of steps per day, and of self-reported PA, with CD and other cardiovascular risk factors using pooled data. Cohort-specific correlations are reported in Supplementary Table 1 showing consistent results. Steps per day and total PA were negatively associated with RHR, insulin and triglycerides and positively associated with HDL-C, but not with CD. Among CDAH participants, self-reported time spent on walking was also not associated with CD (men $P = 0.431$, women $P = 0.968$). Although the associations of outcomes with total PA or total vigorous PA remained significant, they were largely reduced after adjustment for the vigorous leisure-time component of PA (not shown). Only vigorous leisure-time PA was positively associated with CD.

Because only vigorous leisure-time PA was associated with CD, we further investigated this association. Supplementary Table 2 shows that participants with greater vigorous leisure-time PA had greater mean values of CD. Whereas steps per day and self-reported walking and moderate PA (not shown) were not associated with CD, participants spending at least 1 h per week in vigorous leisure-time PA had a lower vascular age of approximately 6.6 years (CDAH men), 1.0 year (CDAH women), 2.7 years (Young Finns men) and 3.2 years (Young Finns women) than those who did not. Based on consistent findings from parallel analyses, Table 3 shows pooled-data analyses adjusting for cohort and age, which presents associations of greater levels of vigorous leisure-time PA with lower risk of having low arterial distensibility (see Materials and Methods). In contrast, greater steps per day was not associated with risk of having low arterial distensibility (CDAH men $P = 0.868$, women $P = 0.254$; Young Finns men $P = 0.883$, women $P = 0.161$). Adjustment for socio-economic status, smoking and alcohol consumption, and muscular strength (CDAH only), did not change our findings (not shown).

Compared with BMI, MAP and blood biomarkers, RHR was most strongly correlated with CD (CDAH men $r = -0.33$ women $r = -0.24$; Young Finns men $r = -0.30$ women $r = -0.30$; $P < 0.001$). To investigate the possible pathways by which participation in vigorous leisure-time PA may influence CD, Table 4 presents the estimated effects of participation in vigorous leisure-time PA on CD with adjustment for RHR and other relevant factors. While adjustment for MAP, BMI or insulin, HDL-C, LDL-C and triglycerides reduced slight-to-moderately the estimated effect of vigorous leisure-time PA on CD, adjustment for RHR substantially reduced this association by 100% among both men and women. Additional adjustment for MAP, BMI or blood biomarkers after adjustment for RHR provided small additional changes to the regression coefficients produced by adjustment for RHR. Cohort-specific analyses are reported in Supplementary Table 3 that shows similar results.

DISCUSSION

Our principal findings were as follows. First, vigorous leisure-time PA, but not total PA or less intensive forms of PA, was associated with greater CD. Second, our findings for the first time suggest that participation in vigorous leisure-time PA may be associated with CD (or delay in age-related arterial stiffening) by reducing RHR. Third, also for the first time, our findings from large population-based samples of younger adults showed that pedometer measured steps per day was not associated with CD. These findings were independent of age, MAP, BMI, biochemical markers, socio-economic status, smoking and alcohol consumption.

Our study included only young to mid-aged adults who did not have the low levels of arterial distensibility typically found among

Table 2 Spearman correlation of different measures of physical activity with carotid artery distensibility and other cardiovascular risk factors

	CD	HR	MAP	Insulin	Glucose	HDL-C	LDL-C	Triglycerides
Men								
Steps per day	0.00	−0.12***	−0.02	−0.14***	−0.03	0.11***	0.01	−0.09***
Total PA[a]	−0.02	−0.05*	0.01	−0.15***	0.01	0.06**	0.03	0.00
Leisure vig. PA[b]	0.07**	−0.21***	−0.02	−0.15***	−0.10***	0.10***	−0.10***	−0.09***
Women								
Steps per day	0.03	−0.13***	−0.00	−0.12***	−0.05*	0.10***	−0.05*	−0.10***
Total PA[a]	−0.01	−0.05*	−0.01	−0.03	0.01	0.02	0.03	−0.01
Leisure vig. PA[b]	0.05*	−0.17***	0.01	−0.11***	−0.05*	0.09***	−0.06**	−0.08***

Abbreviations: CD, carotid distensibility; HDL-C, high-density lipoprotein cholesterol; HR, heart rate; LDL-C, low-density lipoprotein cholesterol; MAP, mean arterial pressure; MET, metabolic equivalent of task; PA, physical activity.
All analyses were adjusted for cohort. *$P<0.05$; **$P<0.01$; ***$P<0.001$.
[a]Total MET.hour per week.
[b]Levels of participation in vigorous leisure-time physical activities.

Table 3 Relative risks of having low arterial distensibility by levels of participation in vigorous leisure-time physical activity in the two samples (pooled-data analysis)

	Men			Women		
	n/N	RR	(95% CI)	n/N	RR	(95% CI)
Vigorous leisure-time PA						
None	93/744	1.00	Ref	103/881	1.00	Ref
Any	83/1047	0.62	(0.46, 0.82)	115/1284	0.73	(0.56, 0.96)
Vigorous leisure-time PA						
None	93/744	1.00	Ref	103/881	1.00	Ref
<2 h per week	33/351	0.73	(0.50, 1.07)	54/533	0.83	(0.60, 1.15)
2–3 h per week	31/404	0.60	(0.40, 0.88)	36/486	0.60	(0.40, 0.87)
>3 h per week	19/292	0.51	(0.32, 0.83)	25/265	0.73	(0.50, 1.06)
		$P_{trend}=0.003$			$P_{trend}=0.03$	

Abbreviations: RR, relative risk; PA, physical activity.
Low arterial distensibility was defined by having carotid distensibility <10th percentile specific for each sample, each sex and each year of age.
All models were adjusted for age and cohort.

Table 4 Regression of carotid distensibility on levels of participation in vigorous physical activity during leisure time, with adjustment for heart rate and other relevant factors

	Carotid distensibility (%/10mm Hg)	
	Men	Women
	β (95% CI)	β (95% CI)
Unadjusted	0.40 (0.14, 0.66)	0.41 (0.09, 0.73)
Adjusted for		
Age	0.34 (0.08, 0.60)	0.36 (0.04, 0.67)
Age, MAP	0.34 (0.08, 0.60)	0.36 (0.05, 0.67)
Age, BMI	0.28 (0.03, 0.54)	0.23 (0.01, 0.49)
Age, Biomarkers[a]	0.28 (0.02, 0.54)	0.21 (0.00, 0.40)
Age, RHR	−0.05 (−0.30, 0.20)	−0.03 (−0.34, 0.27)
Age, RHR, MAP	−0.01 (−0.26, 0.24)	0.01 (−0.28, 0.32)
Age, RHR, BMI	−0.07 (−0.32, 0.18)	−0.15 (−0.46, 0.15)
Age, RHR, Biomarkers[a]	−0.11 (−0.37, 0.14)	−0.07 (−0.38, 0.23)

Abbreviations: BMI, body mass index; CDAH, the Childhood Determinants of Adult Health study; CI, confidence intervals; MAP, mean arterial pressure; HDL, low-density lipoprotein; LDL, low-density lipoprotein; RHR, resting heart rate; Young Finns, the Cardiovascular Risk in Young Finns study.
All analyses were adjusted for cohort.
[a]Including adjustment for insulin, HDL-cholesterol, LDL-cholesterol and triglycerides.

older people. Light-to-moderate PA has been found to increase arterial distensibility among old adults,[33] but more vigorous PA may be required to increase the higher levels of arterial distensibility among younger adults as shown in our study. This is consistent with a study of a small sample of young adults.[13] The same logic may explain the weaker association found for CDAH women in our study. Women in this age range have higher CD than men. This was observed in both the CDAH and Young Finns samples, and also in other studies.[34,35] In our study, CDAH women had the highest mean level of CD compared with CDAH men and Young Finns men and women and, as shown in Supplementary Table 2, even CDAH women who did not do any vigorous leisure-time PA had greater CD than the CDAH men who spent more than 3 h per week engaged in vigorous leisure-time PA. Thus, any benefits for CD of participation in vigorous PA may have been marginal or undetectable.

Current recommendations for PA[8] reflect the evidence that cardiovascular risk can be reduced by either vigorous PA or moderate PA but with longer time required for moderate PA to achieve the same benefits. In our study, the benefits of PA in respect of greater CD were confined to vigorous leisure-time PA, and associations with RHR and CRF were greater for this type of PA as well. Whereas light-to-moderate PA was not associated with greater CD, participants who spent at least 1 h per week on vigorous PA as described by the guideline[8] had younger vascular age than those who did not. Although

our findings do not contradict the benefits of light-to-moderate PA such as walking for cardiovascular health, they suggest that an increase in arterial distensibility among young to mid-aged adults may be best achieved by participation in vigorous PA and, are consistent with other evidence of vigorous PA being associated with greater cardioprotective benefits.[12]

In previously published work using the Australian sample,[14] we found a positive relationship of CRF with CD that was mediated by RHR. This finding was not due to RHR being a surrogate marker of CRF and was previously discussed.[14] In this study, RHR consistently mediated the positive relationship of vigorous leisure-time PA with CD in each of the Australian and Finnish sample. Though not completely understood, high RHR may increase mechanical load on the arterial wall by exposure to higher mean pressure and increase cyclic shear stress by shortening the diastolic period.[36] This might lead to greater arterial wall stiffness possibly by promoting vascular smooth muscle cell growth and collagen deposition.[36] Using data from CDAH, we found that stroke volume was negatively associated with RHR, but was not related to CD. This again suggests that the lower arterial distensibility associated with high RHR may be due to remodelling of the arterial wall.

This study used two large population-based samples of adults in Australia and Finland on whom standardized measurements were made of an extensive range of study factors. Despite many cultural and environmental differences in the two countries, the very consistent results from the two populations strengthened the external validity of our findings. Using similar standardized protocols for physical measurements (including CD) in the two cohorts was another strength of this study. Although transducers with different frequencies were used, the coefficients of variation between these methods were very similar,[16] suggesting comparable accuracy. Combining data on both self-reported and objectively-measured PA helps to clarify the beneficial effects of PA at different intensities for cardiovascular health. The validity of self-reported PA in our study was confirmed by its strong association with objectively-measured CRF. We were able to somewhat differentiate endurance training from strength training, which may have adverse effects on arterial distensibility,[37] by accounting for muscular strength (in the CDAH sample). A limitation of our study was the use of brachial, instead of carotid, pulse pressure to calculate CD. This is likely to have resulted in an underestimation of the reported association between RHR and CD because the most physically-active people (with higher CD and lower RHR) would also be more likely to have the greatest systolic and pulse pressure amplification (higher brachial compared with central systolic and pulse pressure). The higher estimated values for SBP may therefore underestimate the calculated CD. The cross-sectional design of this study, however, limits the causal inferences concerning the relationship of vigorous PA with CD. We cannot rule out the possibility of reverse causation whereby participants with stiffer arteries might do less vigorous PA. However, our findings on these generally-healthy individuals who were unaware of their levels of arterial distensibility link well with previous findings to suggest that young and mid-aged adults may acquire additional benefits of increased arterial distensibility by participation in vigorous leisure-time PA; a benefit mediated *via* lower RHR.

In summary, our findings provide further evidence to support the recommendation of vigorous PA for cardiovascular health benefits beyond those achieved through light-to-moderate PA such as walking in young to mid-aged adults and, for the first time, suggest that participation in vigorous PA may increase arterial distensibility through lower RHR.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Supplementary Information accompanies the paper on Hypertension Research website (http://www.nature.com/hr)