Cardiac Response to Exercise in Normal Ageing: What Can We Learn from Masters Athletes?

A Beaumont1,*, A Campbell1, F Grace2 and N Sculthorpe1

1Institute of Clinical Exercise and Health Science, University of the West of Scotland, G72 0LH, Scotland; 
2Department of Human Movement and Sports Sciences, Federation University, University Drive, Mt Helen, Ballarat, VIC 3350, Australia

Abstract: Background: Ageing is associated with an inexorable decline in cardiac and vascular function, resulting in an increased risk of Cardiovascular Disease (CVD). Lifestyle factors such as exercise have emerged as a primary therapeutic target in the prevention of CVD, yet older individuals are frequently reported as being the least active, with few meeting the recommended physical activity guidelines. In contrast, well trained older individuals (Masters athletes) have superior functional capacity than their sedentary peers and are often comparable with young non-athletes. Therefore, the 'masters' athlete may be viewed as a unique non-pharmacological model which may allow researchers to disentangle the inexorable from the preventable and the magnitude of the unavoidable 'true' reduction in cardiac function due to ageing.

Conclusion: This review examines evidence from studies which have compared cardiac structure and function in well trained older athletes, with age-matched controls but otherwise healthy.

Keywords: Systolic function, diastolic function, cardiac remodelling, healthy ageing, athletes, cardiac response.
1. INTRODUCTION

Improvements in long-term survival have increased the number of older, and elderly individuals worldwide. Indeed, the World Health Organisation estimates that the number of those aged over 60 years of age has doubled since 1980, and will triple by 2050 [1]. Consequently, health span is emerging as a critical public health challenge of our generation. Despite significant improvements in the treatment of Cardiovascular Disease (CVD), it remains the main cause of mortality worldwide [2] and accounts for almost one-third of globally mortality [3]. Moreover, for those who survive with CVD, there are substantial costs financially [4] and in reduced quality of life and reduced functional capacity [5]. While advances in healthcare and survival are welcome, the continued burden of cardiovascular morbidity is substantial. In the UK alone, there are an estimated 7 million people coping with ongoing CVD, requiring more than £9 billion in health care costs [6].

Modifiable lifestyle factors such as exercise and Physical Activity (PA) have emerged as primary therapeutic targets in the prevention of CVD, with extensive epidemiological, pre-clinical, and human interventional studies to support its efficacy [7]. Multiple lines of evidence indicate that those individuals who are most active enjoy superior cardiac function, as well as lower levels of systemic inflammation and oxidative stress [8-11]. Correspondingly, this has resulted in a wealth of health promotion recommendations promoting PA for both children and adults [12, 13]. Despite these such recommendations, older individuals are frequently reported as being the least active, with 1 in four adults failing to meet the weekly PA guidelines for health worldwide, of at least 150 minutes of moderate or 75 minutes of vigorous intensity exercise [14], rising to 85 to 90% of older adults in many developed countries [15].

In contrast, investigations of ageing athletes frequently report that relative to their sedentary counterparts, they exhibit high levels of cardiovascular reserve (i.e. Stroke Volume (SV) and a maximal cardiac output; [16]) while simultaneously presenting with minimal risk
factors for CVD [11]. In studies of cardiovascular function, endurance trained masters athletes have superior functional capacity, cardiovascular reserve, than their sedentary peers, which are comparable with much younger non-athletes [17, 18]. In this respect, the ‘masters athlete’ may be viewed as a unique non-pharmacological model which may allow researchers to disentangle the inexorable from the preventable effects of ageing on cardiac and vascular health. A ‘masters’ or ‘veteran’ athlete has been defined as an individual older than 45 or 50 years of age competing regularly in endurance events [19, 20]. A meta-analysis has been performed on structural and functional cardiac adaptation in younger athletes up to 45 years of age [21], therefore, the present review set out to summarise the available literature regarding the effect of exercise on cardiac health in normal ageing, and with specific reference to comparisons between sedentary individuals and masters athletes ≥ 45 years of age.

2. CARDIAC STRUCTURE AND FUNCTION IN RELATION TO EXERCISE AND AGEING

2.1. LV Diastolic Function

2.1.1. The Impact of Healthy Ageing on Diastolic Function

Diastolic function may be divided into 2 components, compliance and relaxation [22]. Myocardial relaxation concerns myocyte calcium handling, whereas ventricular compliance is determined by the interaction of compliant cardiac muscle and less compliant (stiff) connective tissue and extracellular matrix [22]. The inevitability of chronological sedentary yet, healthy ageing seemingly leads to a gradual decline in LV compliance until approximately 64 years of age, at which point LV stiffening may be deemed complete [23]. Similarly, with progressive age, early diastolic function determined by Doppler indices of LV diastolic function show reduced early (E) inflow velocity, ratio of early-to-late inflow velocity (E/A) [24], early
diastolic tissue velocity (e’), and gradual increases in the Isovolumic Relaxation Time (IVRT) and time constant of isovolumic pressure decay (Tau) [25]. Collectively, these functional changes highlight a worsening of LV diastolic function inherent to the ageing process.

2.1.2. Healthy Ageing and Diastolic Function in Relation to Exercise

Chronic endurance exercise consisting of multiple years of continued training preserves LV compliance [26], which may be ‘dose’ dependant [27]. In healthy seniors aged >64 years, Bhella et al. [27] found an exercise dose of at least 4 to 5 sessions per week, categorised as ‘committed exercisers’, was sufficient to prevent the age-associated increases in LV stiffness and decreases in distensibility and compliance. Nonetheless, 1 year of aerobic exercise training in previously sedentary, older (71 ± 3 years) individuals did not alter LV compliance or stiffness and therefore, it is possible that exercise initiation prior to reaching ‘older’ age is necessary to circumvent the detrimental impact of ageing [28]. To advance this theory, mitral inflow and tissue velocity indices were not different between sedentary older men (59 ± 3 years) and exercisers who either began exercising prior to 30 years of age or after 40 years of age, however, LV end-systolic elastance (E\textsubscript{LV}) was lower in both trained groups compared with their untrained counterparts, suggesting a less stiff ventricle in the trained groups [29].

Long term exercise does not prevent the gradual decline in resting global diastolic function associated with ageing, as measured by conventional Doppler mitral inflow or tissue velocities [30-38]. Nevertheless, when compared with controls of the same age, older (>45 years) endurance-trained athletes have shown superior diastolic function with greater E [19, 37-39], e’ [19, 22, 36, 40], lower late mitral inflow velocity (A) [34-36, 40-44], lower late mitral annular tissue velocity (a’) [35, 45] and collectively, greater e’/a’ [19, 35, 40] and E/A (Table 1). Equally, in older recreationally active, leisure time athletes, of which sporting discipline was unknown, E/A was greater in trained than untrained [46, 47]. Indeed, the heart
rate and preload dependence of mitral and tissue velocities are known [48, 49]; bradycardia lengthens the diastolic period and reduces the atrial contribution to filling [35, 50]. Therefore, it is possible that superior diastolic function in older athletes may be mediated, in part, by a lower heart rate and/or (to a lesser extent) higher plasma volume. In contrast, a body of evidence disputes a beneficial influence of endurance based exercise on e’ [29, 35, 38, 41, 45] or global diastolic function, expressed as E/A (Table 1) or e’/a’ [31, 37, 45], between age-matched athletes and controls. Thus, it is unclear at present whether exercise is a useful mitigant of the inevitable age-related decline in global diastolic function when determined by the profiling of mitral inflow and tissue velocities. Differences in the participant characteristics and training habits between cross-sectional investigations may well contribute to the conflicting findings.

Soccer specific training of 3 hours per week for 12 months in previously sedentary seniors (68 years of age) sufficiently increased E/A and e’ by 25% and 12%, respectively, which was not observed during the equivalent strength-based intervention [51]. Similarly, short-term training (12 weeks) elicited an increased [52], or demonstrated a trend toward greater [36] E/A in older adults (>62 years) following High Intensity Interval Training (HIIT); whereas, others found no changes in E/A after 8 weeks HIIT [53]. Nonetheless, 5 days of intensified training in seniors (68 years of age) increased E/A, with the change in E/A significantly related to changes in maximal oxygen uptake (r=0.52, p<0.05) [54]. Beyond mitral inflow velocities, studies have found that following short term interval training in previously sedentary individuals e’ did not change [52, 53], or increased to similar levels as master athletes [36]. Further, after 1 year of vigorous exercise baseline e’ decreased, with the suggestion that the effect of exercise training on e’ is different between master athletes with a life-long history of exercise training and seniors undergoing short term interventions [28]. It must be noted however, that the masters athletes were slightly younger than sedentary seniors
during the cross-sectional comparison and thus, an influence of age on the greater e’ in athletes cannot be ruled out. Nonetheless, taking these findings together, despite some unavoidable decline in diastolic function inherent to progressive ageing and irrespective of the mechanistic underpinning of whether changes reflect altered loading conditions, heart rate or intrinsic functional modifications, these data provide some support for improved diastolic function concomitant with exercise training and/or compared with age-matched sedentary counterparts.

The unidimensional motion of tissue velocities does not provide a full description of the LV movements during diastole [38], the assessment of LV rotational mechanics, namely untwisting, can provide further insight into the intrinsic function of the heart at various stages of the cardiac cycle. Recently, studies of middle-aged (~54-57 years) male athletes [35, 55] reported no training effect on E or e’ at rest but did identify a significantly greater percentage of untwisting during IVRT. This observation is of particular importance considering the percentage of untwist during early diastole declines with age [56], and may, therefore, suggest a preservation of early diastolic function into old age in aerobically trained individuals. Peak untwisting velocity, however, is contrasting between studies, with some observing greater in athletes than controls [55] and others finding comparable between trained and untrained groups [34, 35]. Carrick-Ranson et al. [31] found the larger SV during exercise in older trained men was not the result of faster LV mitral inflow or tissue velocities.

During submaximal exercise, greater E and peak untwisting velocity have been observed in senior trained men than controls [55]. In contrast, Lee et al. [34] reported no change in untwisting velocity from rest to exercise in middle-aged trained men, yet an increase in their age-matched untrained counterparts. Still, the trained group achieved peak untwisting velocity earlier than middle-aged untrained. However, because the peak base-to-apex intraventricular pressure gradient is linearly related to peak untwisting velocity [57], superior untwisting mechanics during exercise would likely facilitate greater LV suction within early diastole and
thereby, support LV filling. Yet, given the heterogeneity between studies to data, future studies reporting Speckle Tracking Echocardiographic (STE) derived untwist mechanics, including peak velocities and temporal analysis, will provide a depth of understanding complimentary to conventionally derived Doppler velocities.

2.2. LV Structure

Normal ageing is associated with an increase in the LV wall thickness, likely manifested by cellular ageing and a gradual loss of cardiomyocytes initiating compensatory increase in cardiomyocyte size (LV hypertrophy) [57]. While several cross-sectional studies have documented larger absolute wall thickness in athletes compared with untrained controls, this is not consistent (Table 1). Baldi et al. [30] reported that LV interventricular septal (IVS) and posterior wall thicknesses were 20-22% greater in older athletes than age-matched controls (65 years), whereas a 5% smaller IVS was noted in the young trained compared with untrained. These data may suggest that athletes of the older population exhibit greater adaptations than younger individuals (26 years). Furthermore, prolonged dynamic exercises principally impose a volume overload challenge upon the LV and as a result, older endurance trained athletes have shown larger LV chamber diameters compared to their untrained counterparts (Table 1). Notably, this is not consistent across available literature. (Table 1). One explanation for the contrasting findings is a reduction in training stimulus (intensity, duration, volume) which occurs with progressive ageing and could therefore contribute [59]. Moreover, despite the recent suggested that trained-untrained differences in LV hypertrophy (LV mass) diminish or even disappear with advancing age in those beyond 45 years of age [60], the majority of studies have reported significantly larger LV Mass (LVM) in trained individuals, expressed as absolute or allometrically scaled to indices of body size (Table 1). However, there are inconsistencies in the allometric scaling of LVM between studies. While most have used body surface area,
some have indexed to fat free mass or height\textsuperscript{2,7}; this may be important and account for some heterogeneity in the differences between athletes and controls. Further, the influence of chronological age on the magnitude of difference in LV mass between athletes and controls requires further clarification.

Studies of continuous aerobic exercise training in previously sedentary, older males or females [53, 61-67] have largely found unchanged LV morphology from pre-to-post training interventions ranging from 2-9 months. In contrast, three studies in older populations (all 68 years of age) found a statistically significant increase in LVM index of 5-18\% following 4-12 months of dynamic exercise training [28, 51, 68] suggestive of an eccentric remodelling [28, 51]. The lack of adaptations in the majority of studies are unlikely to be accounted for by an insufficient exercise intensity since specific HIIT programmes also observed unchanged morphology [53]. Similarly, in a recent study of lifelong sedentary males (63 ± 5 years), Grace et al. [52] reported no changes in LV morphology following six weeks of supervised pre-conditioning exercise, which preceded a further 6 weeks of low-frequency HIIT. The training programme duration would likely elicit some influence on the magnitude of adaptation, however, since structural increases were observed after 4 months of football training (small sided games) in elderly men 65-75 years of age [51], suggests adaptations can occur within short periods of HIIT and thus, the programme duration may not be the sole determinant. Greater exercise stimulus including intensity, session duration and frequency, training programme duration, participant age upon recruitment or an interaction of these factors may be necessary to induce modifications within the LV structure. Additionally, and in consideration of the strong evidence from cross-sectional studies of greater LV mass in older trained than untrained adults, with many years of exercise training, suggesting that adaptation may occur earlier in life and is then maintained into older age with continued aerobic exercise training relative to age-matched controls.
2.3. LV Systolic Function

LV systolic function is most commonly presented as Ejection Fraction (EF) which is preserved at rest with healthy ageing [24, 69]. The majority of cross-sectional data report similar EF (Table 1) or fractional shortening (FS) [30,70-72] between older trained and untrained adults. With advancing age, however, EF at maximal exercise is lower while LV End-Diastolic Volume (LVEDV) increases and this counterbalancing results in a lack of overall net change in SV index [24]. Bouvier et al. [70] reported that EF was similar between master athletes and controls at rest, yet reported a significant training effect of greater EF at maximal exercise in the trained group. EF improved following 8-12 weeks of interval training in older adults [36, 53], which has not been observed following continuous exercise training [53, 73]. Indeed, the change in EF from pre-to-post exercise intervention was linearly related to the change in maximal oxygen uptake ($\dot{V}O_{2\text{max}}$) [53]. Similarly, Fujimoto et al. [28] reported 1-year vigorous exercise training improved $\dot{V}O_{2\text{max}}$ via favourable changes in maximal cardiac performance, without alterations in arterial-venous oxygen difference. However, another HIIT training study in older adults, of shorter duration and less frequency, reported no changes in EF [52], which may suggest that in addition to intensity, total exercise volume is important.

Alternate measures of LV systolic function include the mitral annular systolic tissue velocity (s’) [74], albeit the literature is undecided as to whether this declines which may [30, 35, 36, 38] or not [31, 37] during chronological ageing. The majority of studies have shown homogenous s’ between trained and untrained adults [29, 31, 35, 36, 40, 41, 45]. In addition to tissue velocities, newer methods of assessing LV systolic function have been developed, such as STE, with the advantage of being relatively angle independent and not subjected to the tethering effect [75, 76]. Global Longitudinal Strain (GLS) denotes shortening/deformation about its entire long-axis and when averaged across all LV wall segments is used as a measure of global systolic function [77, 78]. Compared with EF, GLS provides a greater means of
directly assessing contractility and is a more sensitive marker of systolic (dys)function [78]. Unlike EF, GLS decreases across the lifespan in healthy participants [68, 79]. Although Schmidt et al. [41] found 12% greater (negative) GLS in veteran football players (68 years) compared with age-matched controls, the general consensus from other observational studies is a lack of training effect on GLS in ageing athletes [29, 32, 45, 80]. Participant recruitment might offer an explanation to the unique findings of increased GLS by Schmidt et al. [41], where in the veteran footballers (68 years) were still regularly competing throughout the year (26 ± 12 soccer matches) and when compared with participants in the other studies, they were of the oldest age and had the longest training history (52 ± 11 years). Exercise stimulus may also be important. A training study from the same group found that following 12 months of football-specific training in previously lifelong sedentary senior (68 years) males, EF increased and GLS increased (more negative) by 8% [51]. Moreover, recently Howden et al. [81] reported a lifelong (at least 25 years) exercise training dose of at least 4 sessions per week in seniors (>60 years) prevented the age-related decline in GLS. Following adjustment for LVEDV however, the training effect was abrogated which, as noted by the authors, highlights the importance of training related changes in LV filling volume in preserving systolic function with ageing. In particular, at similar EDV, GLS was significantly lower in the trained than untrained adults [81]. Taken together, exercise training may improve systolic function. Yet more longitudinal studies are required with GLS as an adjunct to conventional measures as it might offer a more sensitive determinant of interactions between exercise and ageing.

Beyond longitudinal shortening during contraction, the LV also rotates along its long-axis [77]. Systolic twist determined by the opposing rotations at the base and apex in clockwise and counterclockwise directions, respectively [77], increases stepwise with age in a general population of healthy individuals [55]. Maufrais et al. [35] documented a lower magnitude of resting twist in senior athletes compared with controls, suggesting a preservation of the age-
related increase in twist, while two studies observed no training effect [34, 54]. With the transition from rest to exercise, Lee et al. [34] found middle-aged aerobic athletes were able to increase twist compared with controls, whereas Maufrais et al. [54] observed no differences between training levels during submaximal cycling. In younger individuals, LV twist increases with submaximal exercise [82, 83], which is closely coupled with exercise SV [84]. The ability to increase LV twist in older athletes in response to a physiological exercise stress would suggest a greater functional capacity to accommodate the heightened cardiovascular demands by modulating LV output. Nonetheless, further assessment of twisting mechanics in older athletes both at rest and during exercise will provide additional, insightful information to advance our understanding of systolic functioning following long-term exercise training in masters athletes.

CONCLUSION

There is growing evidence that undertaking regular exercise training results in improved indices of diastolic performance. In addition, lifelong exercisers exhibit moderate remodelling to support greater SV and cardiac output. However, differences in systolic function are less clear, therefore, much of this comparative data has been acquired at rest, and it is possible that larger differences may be evident during exercise, as the greater functional reserve of masters athletes becomes apparent. There is a need for more observational studies, to include exercise measures, as well as wider use of novel imaging technologies within this cohort.

The non-pharmacological model of the 'master athlete' enables researchers to extract the inexorable from the preventable effects of ageing on cardiac structure and function. The superior findings in those who have sustained exercise training into old age, suggest that the waning assumed to occur with age are less precipitous than previously suspected, and that while some functional impairment seems inevitable, partaking in regular exercise may result
in a significant slowing in the rate of decline. However, there is a need for more research to help elucidate the mechanisms of true age-related decline and the mechanisms of decline due to sedentariness and that which can be mitigated by physical exercise. In addition, more data are needed to determine the most effective prescription to improve cardiac function.

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

ACKNOWLEDGEMENTS

Declared none.

REFERENCES

1. WHO. World Health day: Are you ready? What you need to know about aging. Accessed Dec. 2012; 20: 2012.
2. Roth GA, Huffman MD, Moran AE, et al. Global and regional patterns in cardiovascular mortality from 1990 to 2013. Circulation 2015; 132(17): 1667-78.
3. WHO. WHO | Cardiovascular diseases (CVDs) [Internet]. WHO. 2017 [cited 2018 Mar 2]. Available from: http: //www.who.int/mediacentre/factsheets/fs317/en/
4. Zhao Z, Winget M. Economic burden of illness of acute coronary syndromes: Medical and productivity costs. BMC Health Serv Res 2011; 11: 35.
5. Vilahur G, Badimon JJ, Bugiardini R, Badimon L. Perspectives: The burden of cardiovascular risk factors and coronary heart disease in Europe and worldwide. Eur Heart J Suppl2014; 16(supplA): A7-11.
6. British Heart Foundation. CVD Statistics: BHF UK Factsheet [Internet]. 2017. Available from: https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0ahUKEwjSj9fKhs3ZAhVFBMAKHRzxAWcQFggpMAA&url=https%3A%2F%2Fwww.bhf.org.uk%2Fmedia%2Ffiles%2Fresearch%2Fheart-statistics%2Fbhf-cvd-statistics---uk-factsheet.pdf&usg=AOvVaw1dOumSZ3VTfAeRQ7TGFRuD

7. Lavie CJ, Arena R, Swift DL, et al. Exercise and the cardiovascular system: Clinical science and cardiovascular outcomes. Circ Res 2015; 117(2): 207-19.

8. Eskurza I, Monahan KD, Robinson JA, Seals DR. Effect of acute and chronic ascorbic acid on flow-mediated dilatation with sedentary and physically active human ageing. J Physiol 2004; 556(Pt 1): 315-24.

9. Grace FM, Herbert P, Ratcliffe JW, New KJ, Baker JS, Sculthorpe NF. Age related vascular endothelial function following lifelong sedentariness: positive impact of cardiovascular conditioning without further improvement following low frequency high intensity interval training. Physiol Rep 2015; 3(1): e12234.

10. Lesniewski LA, Zigler ML, Durrant JR, et al. Aging compounds western diet-associated large artery endothelial dysfunction in mice: Prevention by voluntary aerobic exercise. Exp Gerontol 2013; 48(11): 1218-25.

11. Seals DR. Edward F. Adolph Distinguished Lecture: The remarkable anti-aging effects of aerobic exercise on systemic arteries. J Appl Physiol 2014; 117(5): 425-39.

12. Kraus WE, Bittner V, Appel L, et al. The national physical activity plan: A call to action from the American Heart Association: A science advisory from the American Heart Association. Circulation 2015; 131(21): 1932-40.

13. Public Health England. One You - Home [Internet]. 2016 [cited 2017 Nov 16]. Available from: https://www.nhs.uk/oneyou
14. The World Health Organization. The World Health Organization Physical Activity Fact Sheet [Internet]. 2017. Available from: http://www.who.int/mediacentre/factsheets/fs385/en/

15. Sparling PB, Howard BJ, Dunstan DW, Owen N. Recommendations for physical activity in older adults. BMJ 2015; 350: h100.

16. Rogers MA, Hagberg JM, Martin WH, Ehsani AA, Holloszy JO. Decline in VO2max with aging in master athletes and sedentary men. J Appl Physiol 1990; 68(5): 2195-9.

17. Grace F, Herbert P, Elliott AD, Richards J, Beaumont A, Sculthorpe NF. High intensity interval training (HIIT) improves resting blood pressure, metabolic (MET) capacity and heart rate reserve without compromising cardiac function in sedentary aging men. Exp Gerontol 2017; [Epub ahead of print].

18. Nowak KL, Rossman MJ, Chonchol M, Seals DR. Strategies for achieving healthy vascular aging. Hypertension 2018; 71(3): 389-402.

19. D’Andrea A, Caso P, Scarafile R, et al. Biventricular myocardial adaptation to different training protocols in competitive master athletes. Int J Cardiol 2007; 115(3): 342-9.

20. Wilson M, O’Hanlon R, Basavarajaiah S, et al. Cardiovascular function and the veteran athlete. Eur J Appl Physiol 2010; 110(3): 459-78.

21. Utomi V, Oxborough D, Whyte GP, et al. Systematic review and meta-analysis of training mode, imaging modality and body size influences on the morphology and function of the male athlete’s heart. Heart 2013; 99(23): 1727-33.

22. Prasad A, Popovic ZB, Arbab-Zadeh A, et al. The effects of aging and physical activity on Doppler measures of diastolic function. Am J Cardiol 2007; 99(12): 1629-36.

23. Fujimoto N, Hastings JL, Bhella PS, et al. Effect of age on left ventricular compliance and distensibility in healthy sedentary humans. J Physiol 2012; 590(8): 1871-80.
24. Lakatta EG, Levy D. Arterial and cardiac aging: major shareholders in cardiovascular disease enterprises: Part II: The aging heart in health: links to heart disease. Circulation 2003; 107(2): 346-54.

25. Carrick-Ranson G, Hastings JL, Bhella PS, et al. Effect of healthy aging on left ventricular relaxation and diastolic suction. Am J Physiol-Heart Circ Physiol 2012; 303(3): H315-22.

26. Arbab-Zadeh A, Dijk E, Prasad A, et al. Effect of aging and physical activity on left ventricular compliance. Circulation 2004; 110(13): 1799-805.

27. Bhella PS, Hastings JL, Fujimoto N, et al. Impact of lifelong exercise “dose” on left ventricular compliance and distensibility. J Am Coll Cardiol 2014; 64(12): 1257-66.

28. Fujimoto N, Prasad A, Hastings JL, et al. Cardiovascular effects of 1 year of progressive and vigorous exercise training in previously sedentary individuals older than 65 years of age. Circulation 2010; 122(18): 1797-805.

29. Matelot D, Schnell F, Kervio G, et al. Cardiovascular benefits of endurance training in seniors: 40 is not too late to start. Int J Sports Med 2016; 37(8): 625-32.

30. Baldi JC, McFarlane K, Oxenham HC, Whalley GA, Walsh HJ, Doughty RN. Left ventricular diastolic filling and systolic function of young and older trained and untrained men. J Appl Physiol Bethesda Md 1985 2003; 95(6): 2570-5.

31. Carrick-Ranson G, Doughty RN, Whalley GA, Walsh HJ, Gamble GD, Baldi JC. The larger exercise stroke volume in endurance-trained men does not result from increased left ventricular early or late inflow or tissue velocities. Acta Physiol Oxf Engl 2012; 205(4): 520-31.

32. Donal E, Rozoy T, Kervio G, Schnell F, Mabo P, Carré F. Comparison of the heart function adaptation in trained and sedentary men after 50 and before 35 years of age. Am J Cardiol 2011; 108(7): 1029-37.
33. Gates PE, Tanaka H, Graves J, Seals DR. Left ventricular structure and diastolic function with human ageing. Relation to habitual exercise and arterial stiffness. Eur Heart J 2003; 24(24): 2213-20.

34. Lee LS, Mariani JA, Sasson Z, Goodman JM. Exercise with a twist: Left ventricular twist and recoil in healthy young and middle-aged men, and middle-aged endurance-trained men. J Am Soc Echocardiogr Off Publ Am Soc Echocardiogr 2012; 25(9): 986-93.

35. Maufrais C, Schuster I, Doucende G, et al. Endurance training minimizes age-related changes of left ventricular twist-untwist mechanics. J Am Soc Echocardiogr Off Publ Am Soc Echocardiogr 2014; 27(11): 1208-15.

36. Molmen HE, Wisloff U, Aamot IL, Stoylen A, Ingul CB. Aerobic interval training compensates age related decline in cardiac function. Scand Cardiovasc J SCJ 2012; 46(3): 163-71.

37. Nottin S, Nguyen L-D, Terbah M, Obert P. Long-term endurance training does not prevent the age-related decrease in left ventricular relaxation properties. Acta Physiol Scand 2004; 181(2): 209-15.

38. Olsen RH, Couppé C, Dall CH, et al. Age-related decline in mitral peak diastolic velocities is unaffected in well-trained runners. Scand Cardiovasc J SCJ 2015; 49(4): 183-92.

39. Cottini E, Giacone G, Cosentino M, Cirino A, Rando G, Vintaloro G. Evaluation of left ventricular diastolic function by pulmonary venous and mitral flow velocity patterns in endurance veteran athletes. Arch Gerontol Geriatr 1996; 22(Suppl 1): 179-86.

40. Galetta F, Franzoni F, Femia FR, Bartolomucci F, Carpi A, Santoro G. Left ventricular diastolic function and carotid artery wall in elderly athletes and sedentary controls. Biomed Pharmacother Biomedicine Pharmacother 2004; 58(8): 437-42.
41. Schmidt JF, Andersen TR, Andersen LJ, et al. Cardiovascular function is better in veteran football players than age-matched untrained elderly healthy men. Scand J Med Sci Sports 2015; 25(1): 61-9.

42. Fleg JL, Shapiro EP, O’Connor F, Taube J, Goldberg AP, Lakatta EG. Left ventricular diastolic filling performance in older male athletes. JAMA 1995; 273(17): 1371-5.

43. Douglas PS, O’Toole M. Aging and physical activity determine cardiac structure and function in the older athlete. J Appl Physiol Bethesda Md 1985 1992; 72(5): 1969-73.

44. Takemoto KA, Bernstein L, Lopez JF, Marshak D, Rahimtoola SH, Chandraratna PA. Abnormalities of diastolic filling of the left ventricle associated with aging are less pronounced in exercise-trained individuals. Am Heart J 1992; 124(1): 143-8.

45. Bohm P, Schneider G, Linneweber L, et al. Right and left ventricular function and mass in male elite master athletes: A controlled contrast enhanced CMR study. Circulation 2016; 133(20): 1927-35.

46. Kneffel Z, Varga-Pintér B, Tóth M, Major Z, Pavlik G. Relationship between the heart rate and E/A ratio in athletic and non-athletic males. Acta Physiol Hung 2011; 98(3): 284-93.

47. Pavlik G, Olexó Z, Osváth P, Sidó Z, Frenkl R. Echocardiographic characteristics of male athletes of different age. Br J Sports Med 2001; 35(2): 95-9.

48. Burns AT, Connelly KA, La Gerche A, et al. Effect of heart rate on tissue doppler measures of diastolic function. Echocardiography 2007; 24(7): 697-701.

49. Galderisi M, Benjamin EJ, Evans JC, et al. Impact of heart rate and PR interval on Doppler indexes of left ventricular diastolic filling in an elderly cohort (the Framingham Heart Study). Am J Cardiol 1993; 72(15): 1183-7.

50. George KP, Naylor LH, Whyte GP, Shave RE, Oxborough D, Green DJ. Diastolic function in healthy humans: Non-invasive assessment and the impact of acute and chronic exercise. Eur J Appl Physiol 2010; 108(1): 1-14.
51. Schmidt JF, Hansen PR, Andersen TR, et al. Cardiovascular adaptations to 4 and 12 months of football or strength training in 65- to 75-year-old untrained men. Scand J Med Sci Sports 2014; 24(Suppl 1): 86-97.

52. Grace F, Herbert P, Elliott AD, Richards J, Beaumont A, Sculthorpe NF. High intensity interval training (HIIT) improves resting blood pressure, metabolic (MET) capacity and heart rate reserve without compromising cardiac function in sedentary aging men. Exp Gerontol 2017; [Epub ahead of print].

53. Hwang CL, Yoo JK, Kim HK, et al. Novel all-extremity high-intensity interval training improves aerobic fitness, cardiac function and insulin resistance in healthy older adults. Exp Gerontol 2016; 82: 112-9.

54. Petrella RJ, Cunningham DA, Paterson DH. Effects of 5-day exercise training in elderly subjects on resting left ventricular diastolic function and VO2max. Can J Appl Physiol Rev Can Physiol Appl. 1997 Feb;22(1):37–47.

55. Maufrais C, Doucende G, Rupp T, et al. Left ventricles of aging athletes: Better untwisters but not more relaxed during exercise. Clin Res Cardiol 2017; 106(11): 884-892.

56. Takeuchi M, Nakai H, Kokumai M, Nishikage T, Otani S, Lang RM. Age-related changes in left ventricular twist assessed by two-dimensional speckle-tracking imaging. J Am Soc Echocardiogr Off Publ Am Soc Echocardiogr 2006; 19(9): 1077-84.

57. Notomi Y. Enhanced ventricular untwisting during exercise: A mechanistic manifestation of elastic recoil described by doppler tissue imaging. Circulation 2006; 113(21): 2524-33.

58. Steenman M, Lande G. Cardiac aging and heart disease in humans. Biophys Rev 2017; 9(2): 131-7.

59. Tanaka H, Seals DR. Endurance exercise performance in Masters athletes: Age-associated changes and underlying physiological mechanisms. J Physiol 2008; 586(Pt 1): 55-63.
60. Pavlik G, Major Z, Csajági E, Jeserich M, Kneffel Z. The athlete’s heart. Part II: Influencing factors on the athlete’s heart: Types of sports and age (review). Acta Physiol Hung 2013; 100(1): 1-27.

61. Spina RJ, Meyer TE, Peterson LR, Villareal DT, Rinder MR, Ehsani AA. Absence of left ventricular and arterial adaptations to exercise in octogenarians. J Appl Physiol Bethesda Md 1985 2004; 97(5): 1654-9.

62. Stewart KJ, Ouyang P, Bacher AC, Lima S, Shapiro EP. Exercise effects on cardiac size and left ventricular diastolic function: Relationships to changes in fitness, fatness, blood pressure and insulin resistance. Heart Br Card Soc 2006; 92(7): 893-8.

63. Sagiv M, Fisher N, Yaniv A, Rudoy J. Effect of running versus isometric training programs on healthy elderly at rest. Gerontology 1989; 35(2-3): 72-7.

64. Haykowsky M, McGavock J, Vonder Muhll I, et al. Effect of exercise training on peak aerobic power, left ventricular morphology, and muscle strength in healthy older women. J Gerontol A Biol Sci Med Sci 2005; 60(3): 307-11.

65. Park SK, Park JH, Kwon YC, Yoon MS, Kim CS. The effect of long-term aerobic exercise on maximal oxygen consumption, left ventricular function and serum lipids in elderly women. J Physiol Anthropol Appl Human Sci 2003; 22(1): 11-7.

66. Pickering GP, Fellmann N, Morio B, et al. Effects of endurance training on the cardiovascular system and water compartments in elderly subjects. J Appl Physiol Bethesda Md 1985 1997; 83(4): 1300-6.

67. Spina RJ, Rashid S, Dávila-Román VG, Ehsani AA. Adaptations in beta-adrenergic cardiovascular responses to training in older women. J Appl Physiol Bethesda Md 1985 2000; 89(6): 2300-5.
68. Levy WC, Cerqueira MD, Abrass IB, Schwartz RS, Stratton JR. Endurance exercise training augments diastolic filling at rest and during exercise in healthy young and older men. Circulation 1993; 88(1): 116-26.

69. Hung C-L, Gonçalves A, Shah AM, Cheng S, Kitzman D, Solomon SD. Age- and sex-related influences on left ventricular mechanics in elderly individuals free of prevalent heart failure clinical perspective. Circ Cardiovasc Imaging 2017; 10(1): e004510.

70. Bouvier F, Saltin B, Nejat M, Jensen-Urstad M. Left ventricular function and perfusion in elderly endurance athletes. Med Sci Sports Exerc 2001; 33(5): 735-40.

71. Child JS, Barnard RJ, Taw RL. Cardiac hypertrophy and function in master endurance runners and sprinters. J Appl Physiol 1984; 57(1): 176-81.

72. Di Bello V, Lattanzi F, Picano E, et al. Left ventricular performance and ultrasonic myocardial quantitative reflectivity in endurance senior athletes: an echocardiographic study. Eur Heart J 1993; 14(3): 358-63.

73. Fujimoto N, Hastings JL, Carrick-Ranson G, et al. Cardiovascular effects of 1 year of alagebrium and endurance exercise training in healthy older individuals clinical perspective. Circ Heart Fail 2013; 6(6): 1155-64.

74. Lang RM, Badano LP, Mor-Avi V, et al. Recommendations for cardiac chamber quantification by echocardiography in adults: An update from the American Society of Echocardiography and the European Association of Cardiovascular Imaging. Eur Heart J Cardiovasc Imaging 2015; 16(3): 233-71.

75. Mor-Avi V, Lang RM, Badano LP, et al. Current and evolving echocardiographic techniques for the quantitative evaluation of cardiac mechanics: ASE/EAE consensus statement on methodology and indications endorsed by the Japanese Society of Echocardiography. Eur J Echocardiogr 2011; 12(3): 167-205.
76. Blessberger H, Binder T. Two dimensional speckle tracking echocardiography: Basic principles. Heart 2010; 96(9): 716-22.

77. Bansal M, Kasliwal RR. How do I do it? Speckle-tracking echocardiography. Indian Heart J 2013; 65(1): 117-23.

78. Smiseth OA, Torp H, Opdahl A, Haugaa KH, Urheim S. Myocardial strain imaging: how useful is it in clinical decision making? Eur Heart J 2016; 37(15): 1196-207.

79. Kaku K, Takeuchi M, Tsang W, et al. Age-related normal range of left ventricular strain and torsion using three-dimensional speckle-tracking echocardiography. J Am Soc Echocardiogr Off Publ Am Soc Echocardiogr 2014; 27(1): 55-64.

80. Maessen MF, Eijsvogels TM, Stevens G, van Dijk AP, Hopman MT. Benefits of lifelong exercise training on left ventricular function after myocardial infarction. Eur J Prev Cardiol 2017; 24(17): 1856-66.

81. Howden EJ, Carrick-Ranson G, Sarma S, Hieda M, Fujimoto N, Levine BD. Effects of sedentary aging and lifelong exercise on left ventricular systolic function. Med Sci Sports Exerc 2017; 50(3): 494-501.

82. Beaumont A, Hough J, Sculthorpe N, Richards J. Left ventricular twist mechanics during incremental cycling and knee extension exercise in healthy men. Eur J Appl Physiol 2017; 117(1): 139-50.

83. Doucende G, Schuster I, Rupp T, et al. Kinetics of left ventricular strains and torsion during incremental exercise in healthy subjects: The key role of torsional mechanics for systolic-diastolic coupling. Circ Cardiovasc Imaging 2010; 3(5): 586-94.

84. Stohr EJ, Gonzalez-Alonso J, Shave R. Left ventricular mechanical limitations to stroke volume in healthy humans during incremental exercise. AJP Heart Circ Physiol 2011; 301(2): H478-87.
85. Galetta F, Franzoni F, Santoro G, et al. QT dispersion in elderly athletes with left ventricular hypertrophy. Int J Sports Med 2003; 24(4): 233-7.

86. Giada F, Bertaglia E, De Piccoli B, et al. Cardiovascular adaptations to endurance training and detraining in young and older athletes. Int J Cardiol 1998; 65(2): 149-55.

87. Jungblut PR, Osborne JA, Quigg RJ, et al. Echocardiographic Doppler evaluation of left ventricular diastolic filling in older, highly trained male endurance athletes. Echocardiogr Mt Kisco N 2000; 17(1): 7-16.

88. Kozakova M, Galetta F, Gregorini L, et al. Coronary vasodilator capacity and epicardial vessel remodeling in physiological and hypertensive hypertrophy. Hypertens Dallas Tex 1979 2000; 36(3): 343-9.

89. Lindsay MM, Dunn FG. Biochemical evidence of myocardial fibrosis in veteran endurance athletes. Br J Sports Med 2007; 41(7): 447-52.

90. Miki T, Yokota Y, Seo T, Yokoyama M. Echocardiographic findings in 104 professional cyclists with follow-up study. Am Heart J 1994; 127(4): 898-905.

91. Nishimura T, Yamada Y, Kawai C. Echocardiographic evaluation of long-term effects of exercise on left ventricular hypertrophy and function in professional bicyclists. Circulation 1980; 61(4): 832-40.

92. Northcote RJ, McKillop G, Todd IC, Canning GP. The effect of habitual sustained endurance exercise on cardiac structure and function. Eur Heart J 1990; 11(1): 17-22.

93. Seals DR, Hagberg JM, Spina RJ, Rogers MA, Schechtman KB, Ehsani AA. Enhanced left ventricular performance in endurance trained older men. Circulation 1994; 89(1): 198-205.

94. Vianello A, Caponi L, Franzoni F, et al. Role of matrix metalloproteinases and their tissue inhibitors as potential biomarkers of left ventricular remodelling in the athlete’s heart. Clin Sci Lond Engl 1979 2009; 117(4): 157-64.
Table 1. Summary of studies including echocardiographic derived left ventricular structure, systolic and diastolic function in athletes and controls.

| Study (Year of Publication) | Participant Characteristics | Echocardiographic Measures |
|-----------------------------|----------------------------|---------------------------|
|                             | Sport (Gender- M/F)        | Age (Years)               | Wall Thickness | LVEDD | LVM | E/A | EF |
|                             |                            |                           | IVS   | PWT   | MWT |       |     |
| Baldi et al. [30]           | Controls (M)               | 65.7 ± 3.7                | ↔     | ↔     | ↑   | ↑*   | ↔   |
|                             | Aerobic (M)                | 65.2 ± 4.2                | ↔     | ↔     | ↑   | ↑*   | ↔   |
| Bhella et al. [27]          | Controls (M+F)             | 68.8 ± 5.1                |       |       |     |       |     |
|                             | Endurance (M+F)            | 67.8 ± 2.9                | ↔     |       |     |       |     |
| Bohm et al. [45]            | Controls (M)               | 46.0 ± 9.0                | ↑      | ↑      | ↑   |       |     |
|                             | Runners, rowers, triathletes (M) | 47.0 ± 8.0 | ↑      | ↑      | ↑   |       |     |
| Bouvier et al. [70]         | Controls (-)               | 74.9 ± 2.4                | ↔     | ↑      | ↔   | ↔*   | ↑   |
|                             | Orienteers, runners (M)    | 72.8 ± 2.9                | ↔     | ↑      | ↔   | ↔*   | ↑   |
| Carrick-Ranson et al. [31]  | Controls                   | 66.0 ± 5.0                | ↔     | ↑      | ↑   |       |     |
|                             | Cyclists, runners, dual/triathletes (M) | 66.0 ± 4.0 | ↔     | ↑      | ↑   |       |     |
| Child et al. [71]           | Controls (M)               | 56.3 ± 7.8                | ↑*    | ↑*    | ↑*  | ↑*    | ↑*  |
|                             | Runners (M)                | 53.7 ± 10.6               | ↑*    | ↑*    | ↑*  | ↑*    | ↑*  |
| Cottini et al. [39]         | Controls (-)               | 61.0 ± 7.0                | ↔     | ↔     | ↔   | ↑     | ↑   |
|                             | Aerobic (-)                | 60.0 ± 10.0               | ↔     | ↔     | ↔   | ↑     | ↑   |
| D’Andrea et al. [19]        | Controls (M)               | 47.4 ± 2.2                | ↔     | ↔     | ↑   | ↑*   | ↑   |
|                             | Swimmers (M)               | 48.2 ± 3.4                | ↔     | ↑     | ↑   | ↑*   | ↑   |
| Di Bello et al. [72]        | Controls (M)               | 69.7 ± 8.4                | ↑      | ↑      | ↑   | ↔*   | ↑   |
|                             | Runners (M)                | 65.7 ± 7.1                | ↔     | ↑*    | ↑   | ↔   | ↑   |
| Donal et al. [32]           | Controls (M)               | 58.9 ± 8.6                | ↑      | ↑      | ↑   | ↔   | ↔   |
|                             | Cyclists (M)               | 61.5 ± 5.6                | ↑      | ↑      | ↑   | ↔   | ↔   |
| Douglas and O’Toole. [43]   | Controls (M+F)             | 65.0 ± 6.0                | ↔     | ↑      | ↔   | ↔*   | ↑   |
|                             | Ultra-endurance (M+F)      | 58.0 ± 6.0                | ↔     | ↑*     | ↔*  | ↑   |     |
| Fleg et al. [42]            | Controls (M)               | 63.0 ± 6.0                | ↔*    | ↔*    | ↔*  | ↔*   | ↔*  |
|                             | Runners (M)                | 65.0 ± 8.0                | ↔*    | ↔*    | ↔*  | ↔*   | ↔*  |
| Galetta et al. [85]         | Controls (M)               | 66.9 ± 4.6                | ↑      | ↑      | ↑   | ↔*   | ↔   |
|                             | Runners (M)                | 67.6 ± 4.5                | ↑      | ↑      | ↑   | ↔*   | ↔   |
| Galetta et al. [40]         | Controls (M)               | 68.3 ± 3.2                | ↑      | ↑      | ↑   | ↑*   | ↔   |
|                             | Runners (M)                | 69.4 ± 3.8                | ↑      | ↑      | ↑*  | ↑*   | ↔   |
| Gates et al. [33]           | Controls (M)               | 65.0 ± 6.6                | ↑*    | ↑*    | ↑*  | ↑*   | ↑*  |
|                             | Aerobic (M)                | 68.0 ± 6.9                | ↑*    | ↑*    | ↑*  | ↑*   | ↑*  |
| Giada et al. [86]           | Controls (M)               | 58.0 ± 6.0                | ↑*    | ↑*    | ↑*  | ↑*   | ↔   |
|                             | Cyclists (M)               | 55.0 ± 5.0                | ↑*    | ↑*    | ↑*  | ↑*   | ↔   |
| Grace et al. [52]           | Controls (M)               | 62.7 ± 5.2                | ↔     | ↔     | ↔   | ↔*   | ↔   |
|                             | Endurance (M)              | 61.1 ± 5.4                | ↔     | ↔     | ↔*  | ↔   | ↔   |
| Jungblut et al. [87]        | Controls (M)               | 69.0 ± 3.0                | ↔     | ↔     | ↑   | ↑*   | ↔   |
|                             | Runners (M)                | 69.0 ± 5.0                | ↔     | ↔     | ↑   | ↑*   | ↔   |
| Study (Year of Publication) | Participant Characteristics | Echocardiographic Measures |
|----------------------------|-----------------------------|---------------------------|
|                            | Sport (Gender- M/F)         | Age (Years)               | Wall Thickness | LVEDD | LVM | E/A | EF |
|                            |                             |                           | IVS            | PWT   | MWT |
| Kozakova et al. [88]       | Controls (M)                | 46.5 ± 16.0               | ↑↑             | ↔     | ↔   |
|                            | Marathoners, triathletes (M)| 53.1 ± 20.0               | ↑↑             | ↔     | ↔   |
|                            |                             |                           |                |       |     |
| Lee et al. [34]            | Controls (M)                | 54.8 ± 4.3                | ↔↔             | ↔↔    | ↔   |
|                            | Cyclists, triathletes, speed-skaters (M) | 53.8 ± 4.1 | ↔↔             | ↔↔    | ↔   |
| Lindsey and Dunn [89]      | Controls (M)                | 52.0 ± 16.0               | ↑↑             | ↑↑    | ↑*  |
|                            | Runners (M)                 | 52.0 ± 11.4               | ↑↑             | ↑↑    | ↑*  |
| Maessen et al. [80]        | Controls (M)                | 58.0 ± 7.0                | ↔↔             | ↔↔    | ↔   |
|                            | Endurance (M)               | 61.0 ± 7.0                | ↔↔             | ↔↔    | ↔   |
| Matelot et al. [29]        | Controls (M)                | 59.0 ± 3.0                | ↔              | ↑*    | ↔   |
|                            | Runners, cyclists (M)       | 62.0 ± 3.0                | ↑*             | ↔     | ↔   |
| Maufrais et al. [35]       | Controls (-)                | 56.0 ± 6.0                | ↑↑             | ↑↑    | ↑*  |
|                            | Runners, triathletes, cyclists (M) | 54.0 ± 7.0 | ↑↑             | ↑↑    | ↑*  |
| Maufrais et al. [55]       | Controls (M)                | 55.0 ± 8.0                | ↑              | ↑*    | ↔   |
|                            | Cyclists (M)                | 57.0 ± 8.0                | ↑              | ↑*    | ↔   |
| Miki et al. [90]           | Controls (-)                | 49.0 ± 7.6                | ↑*             | ↑*    | ↑*  |
|                            | Cyclists (-)                | 49.4 ± 6.4                | ↑*             | ↑*    | ↑*  |
| Molmen et al. [36]         | Controls (M)                | 71.7 ± 1.3                | ↔↔             | ↔↔    | ↔   |
|                            | Cross-country skiers (M)    | 74.3 ± 1.8                | ↔↔             | ↔↔    | ↔   |
| Nishimura et al. [91]      | Controls (M)                | 46.9 ± 3.3                | ↑↑             | ↑↑    | ↑   |
|                            | Bicyclists (M)              | 45.6 ± 2.3                | ↑↑             | ↑↑    | ↑   |
| Northcote et al. [92]      | Controls (M)                | 56.0 ± 7.0                | ↔              | ↑     | ↔   |
|                            | Runners (M)                 | 56.0 ± 7.0                | ↑              | ↑     | ↔   |
|                            |                             |                           | ↔               | ↑*    | ↑   |
| Nottin et al. [37]         | Controls (M)                | 55.9 ± 4.1                | ↔              | ↑*    | ↔   |
|                            | Cyclists (M)                | 58.6 ± 4.8                | ↔              | ↑*    | ↔   |
|                            |                             |                           | ↔              | ↑*    | ↔   |
| Olsen et al. [38]          | Controls (M)                | 66.3 ± 3.8                | ↑↑             | ↑     | ↑   |
|                            | Runners (M)                 | 65.0 ± 4.6                | ↑              | ↑     | ↑   |
|                            |                             |                           | ↑              | ↑     | ↑   |
| Prasad et al. [22]         | Controls (M+F)              | 69.8 ± 3.0                | ↔↔             | ↑*    | ↑   |
|                            | Marathoners, triathletes, middle-distance runners (M+F) | 67.8 ± 3.0 | ↔↔             | ↑*    | ↑   |
| Seals et al. [93]          | Controls (M)                | 63.0 ± 3.0                | ↑              | ↑     | ↑   |
|                            | Runners (M)                 | 64.0 ± 6.0                | ↑              | ↑     | ↑   |
| Schmidt et al. [41]        | Controls (M)                | 68.2 ± 3.2                | ↔              | ↔     | ↔   |
|                            | Soccer players (M)          | 68.1 ± 2.1                | ↔              | ↔     | ↔   |
| Takemoto et al. [44]       | Controls (M+F)              | 60.0 ± 5.0                | ↑              | ↑     | ↑   |
|                            | Runners (M+F)               | 60.0 ± 7.0                | ↑              | ↑     | ↑   |
| Vianello et al. [94]       | Controls (M+F)              | 57.0 ± 10.0               | ↑              | ↑     | ↑   |
|                            | Marathoners (M+F)           | 58.0 ± 6.5                | ↑              | ↑     | ↓   |

M, male; F, female; IVS, interventricular septal thickness; PWT, posterior wall thickness; MWT, mean wall thickness; LVEDD, left ventricular end-diastolic diameter, LVM, left ventricular mass; E/A, early-to-late mitral inflow velocity; EF, ejection fraction. *, indicates allometrically scaled indices; ↑, significantly greater in athletes as reported by study; ↓,
significantly lower in athletes as reported by study; ↔, no significant difference between athletes and controls as reported by study. Data presented as means ± standard deviation.