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FULL RESEARCH PAPER

Biventricular mechanical pattern of the athlete's heart: comprehensive characterization using three-dimensional echocardiography

Alexandra Fábián [1]*, Adrienn Ujvári[1], Márton Tokodi [1], Bálint Károly Lakatos [1], Orsolya Kiss[1,2], Máté Babity[1], Márk Zámodics[1], Nóra Sydó [1,2], Emese Csulak [1], Hajnalka Vágó[1,2], Liliána Szabó[1], Anna Réka Kiss[1], Andrea Szűcs[1], István Hizoh[1], Béla Merkely[1,2]†, and Attila Kovács [1]*†

[1]Heart and Vascular Center, Semmelweis University, Városmajor str. 68, Budapest H-1122, Hungary; and [2]Department of Sports Medicine, Semmelweis University, Budapest, Hungary

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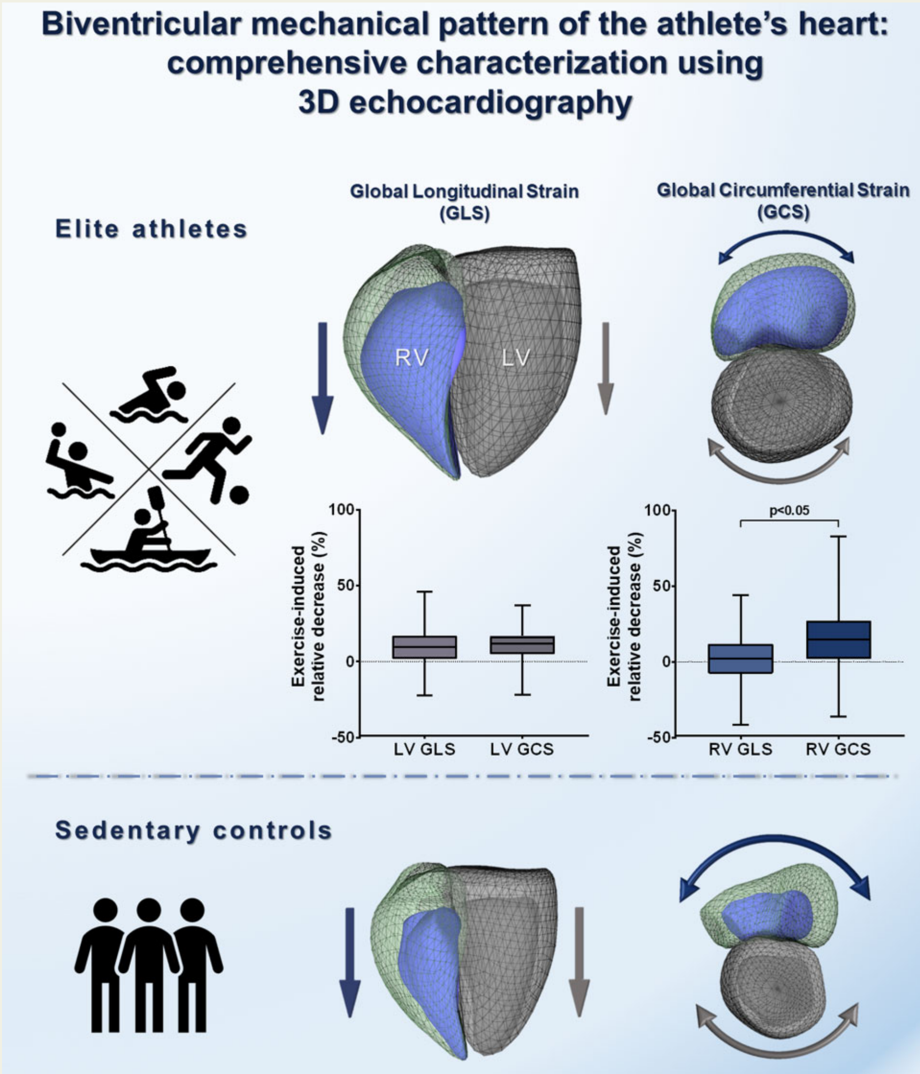
Aims While left ventricular (LV) adaptation to regular, intense exercise has been thoroughly studied, data concerning the right ventricular (RV) mechanical changes and their continuum with athletic performance are scarce. The aim of this study was to characterize biventricular morphology and function and their relation to sex, age, and sports classes in a large cohort of elite athletes using three-dimensional (3D) echocardiography.

Methods and results Elite, competitive athletes ($n = 422$) and healthy, sedentary volunteers ($n = 55$) were enrolled. Left ventricular and RV end-diastolic volumes (EDVi) and ejection fractions (EFs) were measured. To characterize biventricular mechanics, LV and RV global longitudinal (GLS) and circumferential strains (GCS) were quantified. All subjects underwent cardiopulmonary exercise testing to determine peak oxygen uptake (VO_2/kg). Athletes had significantly higher LV and RV EDVi compared with controls (athletes vs. controls; LV EDVi: 81 ± 13 vs. 62 ± 11 mL/m^2, RV EDVi: 82 ± 14 vs. 63 ± 11 mL/m^2; $P < 0.001$). Concerning biventricular systolic function, athletes had significantly lower resting LV and RV EF (LV EF: 57 ± 4 vs. 61 ± 5%; RV EF: 55 ± 5 vs. 59 ± 5%; $P < 0.001$). The exercise-induced relative decrease in LV GLS (9.5 ± 10.7%) and LV GCS (10.7 ± 9.8%) was similar; however, the decrement in RV GCS (14.8 ± 17.8%) was disproportionately larger compared with RV GLS (1.7 ± 15.4%, $P < 0.01$). Right ventricular EDVi was found to be the strongest independent predictor of VO_2/kg by multivariable linear regression.

Conclusion Resting LV mechanics of the athlete's heart is characterized by a balanced decrement in GLS and GCS; however, RV GCS decreases disproportionately compared with RV GLS. Moreover, this mechanical pattern is associated with better exercise capacity.

* Corresponding authors. Tel: +36 20 666 3427, Email: attila.kovacs@med.semmelweis-univ.hu; kovatti@gmail.com (A.K.); Tel: +36 20 666 3510, Email: fabian.alexandra@med.semmelweis-univ.hu (A.F.)
†The last two authors contributed equally to the study.

Graphical Abstract



Keywords Echocardiography • Three-dimensional • Athlete's heart • Right ventricle

Introduction

Regular, intense exercise training is associated with a significantly increased haemodynamic demand and subsequent structural and functional adaptive cardiac changes, commonly referred to as the athlete's heart. In general, dilation of the chambers with increased myocardial mass is observed, and low-normal resting functional measures are also not uncommon findings.[1] Nevertheless, the biventricular morphology and mechanics of athletes are heavily influenced by several factors, such as the different training regimes, sports classes, age, and sex, resulting in a wide spectrum of athletic adaptation.[2] The subsequently different athlete's heart phenotypes are still scarcely characterized, especially in terms of the right ventricular (RV) adaptation, as the majority of current results focuses solely on the left ventricle (LV). Moreover, the physiological continuum between more pronounced cardiac remodelling and better exercise capacity is still not completely understood.

The emergence of advanced techniques, such as deformation imaging and three-dimensional (3D) echocardiography, offers more accurate and detailed quantification of ventricular structure and function. Deformation along the long axis (by longitudinal strain) is a primetime measure of ventricular function; however, the circumferential shortening of both the LV and RV myocardium is also a physiologically important component of systolic performance.[3] In response to different haemodynamic stimuli, ventricular mechanics can change in a complex manner, carrying important diagnostic and prognostic values.[4] Therefore, 3D echocardiography-derived biventricular deformation may also aid to unfold the associations between resting cardiac function and athletic capacity.

Accordingly, the aim of this study was to characterize the impact of sex, age, and different training regimes on biventricular morphology and function, as well as to investigate the correlations between cardiac remodelling and peak exercise capacity in a large, diverse cohort of elite athletes.

Methods

Healthy, competitive, elite athletes were retrospectively identified ($n = 425$) from our centre's complex sports cardiology screening programme; the majority of them ($n = 304$) are members of the national teams in the corresponding age group.[5] As an inclusion criterion, all athletes should have 3D transthoracic echocardiographic images available. A detailed medical history and training regime were obtained along with a standard physical examination and a 12-lead electrocardiogram (ECG). Two-dimensional (2D) and 3D echocardiography and then cardiopulmonary exercise testing (CPET) were performed on all athletes on the same day. We have excluded three athletes due to suboptimal 3D image quality for the analysis of the right ventricle. An age- and sex-matched healthy, sedentary population (no previous participation in intensive training, <3 h of exercise/week) served as the control group. These individuals also underwent the aforementioned screening protocol including CPET. All participants provided written, informed consent to the study procedures. This study is in accordance with the Declaration of Helsinki and approved by the Medical Research Council (ETT-TUKEB No. 13687-0/2011-EKU).

Two- and three-dimensional echocardiography

Transthoracic echocardiographic examinations were performed on commercially available ultrasound systems (E95, 4Vc-D probe, GE Vingmed Ultrasound, Horten, Norway and EPIQ 7, X5-1 probe, Philips Medical Systems, Best, The Netherlands). A standard acquisition protocol consisting of 2D loops from parasternal, apical, and subxiphoid views was applied. Left ventricular (LV) internal diameters, wall thicknesses, and relative wall thickness; left atrial (LA) 2D end-systolic volume; mitral inflow velocities such as early (E) and late diastolic (A) peak velocities, their ratio, and E-wave deceleration time; systolic (s'), early diastolic (e'), and atrial (a') velocities of the mitral lateral and septal annulus; average E/e'; RV basal short-axis diameter, tricuspid annular plane systolic excursion (TAPSE), fractional area change (FAC), pulmonary artery systolic pressure (PASP), and right atrial (RA) 2D end-systolic volume were measured according to current guidelines.[6]

Beyond conventional echocardiographic examination, ECG-gated full-volume 3D datasets reconstructed from four cardiac cycles optimized for the left or right heart were obtained for further analysis on a separate workstation. Three-dimensional datasets focused on the left heart were processed using semi-automated, commercially available software (4D LV-Analysis 3, TomTec Imaging, Unterschleissheim, Germany). We determined LV end-diastolic volume index (EDVi), end-systolic volume index (ESVi), stroke volume index (SVi), and LV mass index (LV Mi). To assess global LV function, ejection fraction (EF), 3D global longitudinal strain (GLS), and 3D global circumferential strain (GCS) were also calculated. Concerning the right heart, we quantified 3D RV EDVi, ESVi, and SVi, EF, and septal and free wall 2D longitudinal strain as well (4D RV-Function 2, TomTec Imaging). Three-dimensional RV GLS and GCS were calculated using the ReVISION software package (Argus Cognitive, Inc., Lebanon, NH, USA) as previously described in detail.[7] Good interobserver and intraobserver variabilities were also previously reported concerning these metrics.[7]

Cardiopulmonary exercise testing

Cardiopulmonary exercise testing for peak oxygen uptake (VO_2 and VO_2/kg) quantification was performed on a treadmill until exhaustion on sport-specific protocols. The volume and composition of the expired gases were analysed breath by breath using an automated cardiopulmonary exercise system (Respiratory Ergostik, Geratherm, Bad Kissingen, Germany). Subjects were encouraged to achieve maximal effort, which was confirmed by respiratory exchange ratio and by reaching the predicted maximal heart rate and a plateau in VO_2.

Statistical analysis

Statistical analysis was performed using dedicated software (StatSoft Statistica, v12, Tulsa, OK, USA). Continuous variables are presented as mean ± standard deviation (SD), whereas categorical variables are reported as frequencies and percentages. After verifying the normal distribution of each variable using the Shapiro–Wilk test, groups were compared with the unpaired Student's t test or Mann–Whitney U test for continuous variables and the χ^2 or Fisher's exact test for categorical variables, as appropriate. Multiple-group comparisons were performed using one-way analysis of variance (ANOVA, with Fisher's *post hoc* test) or Kruskal–Wallis test (with Dunn's *post hoc* test) and two-way analysis of variance (ANOVA, with Fisher's *post hoc* test) with the factors 'Sex' and 'Exercise' and also with the factors 'Age' and 'Sex'. We also calculated the P-value for sex-exercise interaction (P_{Inter}), as well as the P-value for age-sex interaction (P_{Inter}). The Pearson or Spearman test was computed to assess the correlation between continuous variables. Concerning LV GLS, LV GCS, RV GLS, and RV GCS, individual values of athletes were normalized to the mean value of the control group to calculate their relative changes. Univariable and multivariable linear regression analysis (using ordinary least squares) were applied to determine the predictors of VO_2/kg in the entire study cohort. The standard errors of the regression coefficients were calculated from 10 000 bootstrap resamples. A two-sided P-value of <0.05 was considered statistically significant.

The data underlying this article will be shared on reasonable request to the corresponding author.

Results

Athletes vs. sedentary volunteers

Basic anthropometric, haemodynamic data, and training-specific characteristics of the athlete and control groups are summarized in *Table 1*. Most of the athletes participated in mixed and endurance classes of sports, predominantly water polo (34.8%), soccer (30.6%), and swimming (13.3%); however, other types of sports, such as power and skill, were represented as well in our cohort of athletes. Athletes presented with higher values of height, weight, and body surface area compared with the sedentary control group. Athletes also demonstrated significantly higher resting systolic blood pressures and lower diastolic blood pressures and heart rates than controls. Our athletes have been participating in competitive sports for an

Table 1 Baseline and training-specific characteristics of athlete and control groups

	Athletes (*n* = 422)	Controls (*n* = 55)	*P*
Baseline characteristics			
Age (years)	20.1 ± 5.8	20.1 ± 3.2	0.939
Male, *n* (%)	295 (69.9)	31 (56.4)	0.061
Height (cm)	177.9 ± 10.6	171.1 ± 9.5	<0.001
Weight (kg)	72.6 ± 14.7	65.2 ± 13.2	<0.001
BSA (m^2)	1.9 ± 0.2	1.8 ± 0.2	<0.001
SBP (mmHg)	131.9 ± 14.8	123.6 ± 12.5	<0.001
DBP (mmHg)	74.5 ± 9.8	78.2 ± 9.8	0.009
HR (b.p.m.)	67.9 ± 12.5	78.9 ± 15.1	<0.001
Training-specific characteristics			
Type of sport			
Mixed, *n* (%)	293 (69)	—	
Endurance, *n* (%)	88 (21)	—	
Power, *n* (%)	33 (8)	—	
Skill, *n* (%)	8 (2)	—	
Competitive training since (years)	11.9 ± 5.6	—	
Training time (h/week)	15.4 ± 7.3	—	
VO_2 (L/min)	3.8 ± 0.9	2.9 ± 0.8	<0.001
VO_2/kg (mL/kg/min)	52.7 ± 7.7	44.9 ± 7.3	<0.001

Continuous variables are presented as means ± SD; categorical variables are reported as frequencies (%).
BSA, body surface area; DBP, diastolic blood pressure; HR, heart rate; SBP, systolic blood pressure; VO_2, peak oxygen uptake; VO_2/kg, peak oxygen uptake indexed to body weight.

average of 12 years with an average training duration of 15 h/week at the time of the echocardiographic evaluation. The athlete group's CPET-derived peak exercise capacity significantly exceeded the control population's (*Table 1*).

Conventional 2D echocardiographic parameters of athletes and controls are shown in Supplementary material online, *Table S1*. Left ventricular end-diastolic internal diameter, wall thicknesses, and calculated LV mass index were significantly higher in athletes compared with controls. Concerning diastolic function, athletes demonstrated lower transmitral *E*- and *A*-wave velocities along with significantly higher *E/A* ratios; however, there was no difference in deceleration times. Furthermore, mitral annular systolic, early diastolic, and atrial velocities were significantly lower in the athlete population compared with controls, but the average *E/e′* ratio did not differ between the study groups. Two-dimensional LA volume index was significantly higher among athletes. Regarding the right heart, RV basal diameter was larger in the athlete group. Right ventricular FAC showed decreased resting values in athletes; however, TAPSE, RV septal longitudinal strain, and RV free wall longitudinal strain did not differ between the two groups. Two-dimensional RA volume index was significantly higher among athletes (Supplementary material online, *Table S1*).

Detailed 3D echocardiographic characteristics of athletes and controls are summarized in *Table 2*. As expected, there were significant differences between the athlete and the control group concerning LV and RV morphological and functional parameters. Athletes had significantly higher LV and RV EDVi and ESVi values. Similarly, LV Mi, LV SVi, and RV SVi values were higher in athletes compared with controls. In athletes, LV EF, LV GLS, LV GCS along with RV EF, RV GCS showed significantly decreased resting values, in contrast to RV GLS, which did not show difference compared with controls (*Table 2*). The aforementioned results remained the same when comparing male athletes to male controls and female athletes to female controls (Supplementary material online, *Table S2*). Similarly, adolescent athletes (irrespective of sex) already presented with the same pattern of exercise-induced cardiac remodelling as seen in the pooled athlete population when compared with controls (Supplementary material online, *Table S3*).

We have also compared the exercise-induced relative decreases of LV GLS, GCS, and RV GLS and GCS. Left ventricular GLS (average decrease of 10%) and LV GCS (11%) showed a similar, balanced decrease. Meanwhile, the relative decrease of RV GCS (15%) exceeded the decrement in RV GLS (2%, $P < 0.001$) (*Figure 1*).

Sex-specific differences in athletes

We have compared male ($n = 295$) and female ($n = 127$) athletes based on training-specific characteristics and 3D echocardiographic data. The results are shown in Supplementary material online, *Table S4*. There was no significant age difference between the two groups. Male athletes have been participating in competitive sports for longer periods of time; however, females had longer average weekly training duration. Male athletes also showed higher values in CPET-derived peak exercise capacity compared with women. Regarding the 3D echocardiographic results, distinct morphological and functional differences were observed between male and female athletes. Male sex was associated with higher LV and RV EDVi and ESVi. Similarly, LV Mi, LV SVi, and RV SVi values were higher among male athletes compared with females. In male athletes, LV EF, LV GLS, LV GCS along with RV EF, and RV GCS showed significantly decreased resting values, in contrast to RV GLS, which did not differ compared with females (Supplementary material online, *Table S4*).

Adult vs. adolescent athletes

We have also compared adult (>18 years of age, $n = 207$) and adolescent (<18 years of age, $n = 215$) athletes based on training-specific characteristics and 3D echocardiographic data (*Table 3*). Adolescent athletes had an average training duration of 12 h/week. In comparison, adult athletes had an average training duration of 19 h/week. Despite the differences in the training regimes of the two age groups, adolescent athletes' CPET-derived peak exercise capacity significantly exceeded the adult populations'. Adolescent athletes had significantly lower LV EDVi and ESVi and LV Mi values compared with adult athletes; however, LV SVI did not differ between the two age groups. Interestingly, all RV volumes were comparable in the pooled adult vs. adolescent athlete groups; however, if the two sexes were compared, only female adolescents showed similar volumes to adult female athletes (Supplementary material online, *Table S5*). In adolescents, LV EF, LV GLS, and GCS showed higher resting values compared with adults (*Table 3*). In contrast, RV EF and RV GCS did not differ between adults and adolescents, while RV GLS was significantly higher in adolescents compared with adult athletes (*Table 3*).

Table 2 Three-dimensional echocardiographic data of athlete and control groups

	Athletes ($n = 422$)	Controls ($n = 55$)	*P*
Left ventricle			
LV EDVi (mL/m^2)	81.3 ± 13.2	62.2 ± 11.4	<0.001
LV ESVi (mL/m^2)	35.3 ± 7.3	24.3 ± 5.5	<0.001
LV SVi (mL/m^2)	45.9 ± 7.5	37.9 ± 7.2	<0.001
LV Mi (g/m^2)	86.7 ± 15.1	66.0 ± 12.0	<0.001
LV EF (%)	56.7 ± 4.2	61.0 ± 4.5	<0.001
LV GLS (%)	-19.2 ± 2.3	-21.2 ± 2.0	<0.001
LV GCS (%)	-27.7 ± 3.0	-31.0 ± 3.5	<0.001
Right ventricle			
RV EDVi (mL/m^2)	81.6 ± 14.3	62.7 ± 11.2	<0.001
RV ESVi (mL/m^2)	36.7 ± 8.7	25.7 ± 5.3	<0.001
RV SVi (mL/m^2)	44.9 ± 7.3	37.0 ± 7.4	<0.001
RV EF (%)	55.3 ± 4.8	58.9 ± 4.7	<0.001
RV GLS (%)	-21.8 ± 3.4	-22.2 ± 3.6	0.447
RV GCS (%)	-20.9 ± 4.4	-24.5 ± 4.5	<0.001

Continuous variables are presented as means ± SD; categorical variables are reported as frequencies (%).
EDVi, end-diastolic volume index; EF, ejection fraction; ESVi, end-systolic volume index; GCS, global circumferential strain; GLS, global longitudinal strain; LV, left ventricle; Mi, mass index; RV, right ventricle; SVi, stroke volume index.

Differences among sports classes

We have compared the athlete population categorized by different sport disciplines (*Table 4* and Supplementary material online, *Table S6*). The subgroups consisted of athletes participating in mixed ($n = 293$), endurance ($n = 88$), power ($n = 33$), and skill ($n = 8$) sport classes, which classification was based on the relative isometric and isotonic components of exercise according to the recommendations of the European Association of Preventive Cardiology (EAPC) and European Association of Cardiovascular Imaging (EACVI); however, we excluded skill discipline from further analysis due to the very low number of subjects in this subgroup.[8] Power athletes have been competing for the longest time with an average of 17 years, while endurance athletes had significantly longer training durations with an average of 21 h/week. Endurance athletes also exceeded the other groups in terms of peak exercise capacity. Concerning the 3D echocardiographic analysis, LV EDVi and ESVi were comparable between the study groups; however, LV SVi and LV Mi were significantly lower in power athletes than in mixed and endurance athletes. Interestingly,

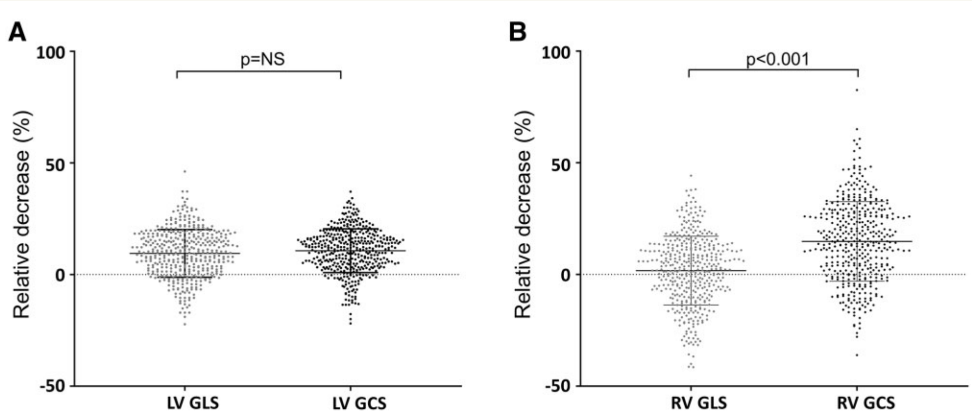


Figure 1 Comparison of the exercise-induced relative decreases of the left ventricular global longitudinal and global circumferential strain—(*A*) and the right ventricular global longitudinal and global circumferential strain—(*B*) in the athlete cohort. Three-dimensional left ventricular global longitudinal strain and left ventricular global circumferential strain ($P = NS$) showed a similar exercise-induced relative decrease; however, the decrement in right ventricular global circumferential strain was disproportionately larger compared with right ventricular global longitudinal strain ($P < 0.001$). NS, nonsignificant.

Table 3 Comparison of adolescent and adult athletes based on training-specific characteristics and 3D echocardiographic data

	Adolescent athletes (*n* = 215)	Adult athletes (*n* = 207)	*P*
Age (years)	15.8 ± 1.4	24.5 ± 5.2	<0.001
Male, *n* (%)	169 (78.6)	126 (60.9)	<0.001
Type of sport			
Mixed, *n* (%)	180 (61.4)	113 (38.6)	—
Endurance, *n* (%)	26 (29.5)	62 (70.5)	—
Power, *n* (%)	3 (9.1)	30 (90.9)	—
Skill, *n* (%)	6 (75)	2 (25)	—
Competitive training since (years)	8.4 ± 3.0	15.5 ± 5.5	<0.001
Training time (h/week)	12.3 ± 6.1	18.6 ± 7.2	<0.001
VO_2/kg (mL/kg/min)	54.4 ± 6.9	50.9 ± 8.2	<0.001
Left ventricle			
LV EDVi (mL/m^2)	80.0 ± 13.0	82.6 ± 13.3	0.040
LV ESVi (mL/m^2)	34.2 ± 7.2	36.4 ± 7.4	0.003
LV SVi (mL/m^2)	45.7 ± 7.3	46.2 ± 7.7	0.418
LV Mi (g/m^2)	83.8 ± 13.5	89.6 ± 16.1	<0.001
LV EF (%)	57.3 ± 3.9	56.1 ± 4.4	0.002
LV GLS (%)	-19.6 ± 2.1	-18.8 ± 2.3	<0.001
LV GCS (%)	-28.0 ± 2.9	-27.4 ± 3.1	0.035
Right ventricle			
RV EDVi (mL/m^2)	80.2 ± 15.2	82.6 ± 14.3	0.104
RV ESVi (mL/m^2)	36.1 ± 8.8	37.2 ± 9.0	0.198
RV SVi (mL/m^2)	44.2 ± 7.9	45.4 ± 7.4	0.098
RV EF (%)	55.3 ± 4.5	55.3 ± 5.1	0.965
RV GLS (%)	-22.3 ± 3.4	-21.3 ± 3.4	0.003
RV GCS (%)	-20.6 ± 4.2	-21.1 ± 4.5	0.195

Continuous variables are presented as means ± SD; categorical variables are reported as frequencies (%).
EDVi, end-diastolic volume index; EF, ejection fraction; ESVi, end-systolic volume index; GCS, global circumferential strain; GLS, global longitudinal strain; LV, left ventricle; Mi, mass index; RV, right ventricle; SVi, stroke volume index.

RV EDVi and RV ESVi were the highest in endurance athletes, while power athletes had lower values of RV EDVi, ESVi, and RV SVi compared with the other groups. In terms of LV function, power athletes demonstrated lower resting values of LV GLS and GCS compared with mixed and endurance athletes. In contrast, resting values of RV EF, RV GLS, and GCS were the lowest in endurance athletes, while power athletes demonstrated the highest resting values of RV GCS compared with the other groups (*Table 4*).

Associations of resting echocardiographic parameters with peak exercise capacity

Univariable correlations between 3D echocardiography-derived parameters and VO_2/kg were assessed using our entire study population. LV volumes, such as LV EDVi ($r = 0.457$, $P < 0.001$), LV ESVi ($r = 0.427$, $P < 0.001$), and LV SVi ($r = 0.389$, $P < 0.001$) as well as LV Mi ($r = 0.397$, $P < 0.001$) correlated significantly with VO_2/kg. Left ventricular functional parameters, namely, LV EF ($r = -0.184$, $P < 0.001$), LV GLS ($r = 0.198$, $P < 0.001$), and LV GCS ($r = 0.169$, $P < 0.001$) showed a weaker inverse correlation with peak exercise capacity. Concerning the right heart, RV EDVi ($r = 0.477$, $P < 0.001$), RV ESVi ($r = 0.449$, $P < 0.001$), and RV SVi ($r = 0.409$, $P < 0.001$) showed significant correlations with VO_2/kg. Right ventricular EF ($r = -0.223$, $P < 0.001$) and RV GCS ($r = 0.221$, $P < 0.001$) had inverse correlations, but RV GLS ($r = 0.018$, $P = 0.688$) did not correlate with VO_2/kg.

We have performed multivariable linear regression analysis (using ordinary least squares) to determine the predictors of VO_2/kg among the 3D echocardiographic LV and RV parameters. Right ventricular EDVi was found to be the strongest independent predictor of VO_2/kg, followed by RV GCS and LV EDVi. The other parameters (LV GLS, LV GCS, LV Mi, and RV GLS) were not significant predictors of peak exercise capacity (Supplementary material online, *Table S7* and *Figure S1*).

Discussion

To the best of our knowledge, this study is the largest to date that investigated both LV and RV remodelling of the athlete's heart using 3D echocardiography. The primary goal of this study was to thoroughly characterize the exercise-induced adaptation of biventricular

Table 4 Comparison of the athlete population categorized by different sport disciplines

	Mixed (n = 293)	Endurance (n = 88)	Power (n = 33)	Overall P
Age (years)	18.8 ± 4.9*,**	22.6 ± 6.7**,***	25.2 ± 5.9*,***	<0.001
Male, n (%)	217 (74.1)*	53 (60.2)***	21 (63.6)	0.031
Competitive training since (years)	10.8 ± 5.1*,**	14.0 ± 5.6**,***	16.6 ± 6.2*,***	<0.001
Training time (h/week)	13.8 ± 7.1*	21.1 ± 6.3**,***	15.3 ± 3.9*	<0.001
VO_2/kg (mL/kg/min)	52.7 ± 7.3*,**	55.4 ± 7.8**,***	45.7 ± 7.3*,***	<0.001
Left ventricle				
LV EDVi (mL/m^2)	81.7 ± 12.6	82.5 ± 15.3	78.1 ± 10.9	0.257
LV ESVi (mL/m^2)	35.3 ± 6.9	36.2 ± 8.8	35.3 ± 5.6	0.579
LV SVi (mL/m^2)	46.4 ± 7.4**	46.3 ± 8.2**	42.8 ± 6.1*,***	0.034
LV Mi (g/m^2)	87.4 ± 14.7**	88.7 ± 16.9**	78.5 ± 9.2*,***	0.002
LV EF (%)	56.9 ± 4.1**	56.3 ± 5.0	54.9 ± 2.9***	0.024
LV GLS (%)	-19.3 ± 2.0**	-19.2 ± 2.5**	-17.7 ± 2.9*,***	0.001
LV GCS (%)	-27.8 ± 2.9**	-27.7 ± 3.5**	-26.4 ± 2.4*,***	0.035
Right ventricle				
RV EDVi (mL/m^2)	81.5 ± 13.9*,**	85.1 ± 16.8**,***	73.6 ± 13.6*,***	0.001
RV ESVi (mL/m^2)	36.4 ± 8.2*,**	39.5 ± 10.3**,***	32.1 ± 8.3*,***	<0.001
RV SVi (mL/m^2)	45.1 ± 7.4**	45.6 ± 8.3**	41.5 ± 6.8*,***	0.022
RV EF (%)	55.5 ± 4.7*	53.9 ± 5.0**,***	56.7 ± 4.7*	0.004
RV GLS (%)	-22.2 ± 3.4*	-20.7 ± 3.1***	-21.5 ± 3.5	0.001
RV GCS (%)	-20.7 ± 4.3**	-20.3 ± 4.1**	-22.5 ± 5.2*,***	0.042

Continuous variables are presented as means ± SD; categorical variables are reported as frequencies (%).
EDVi, end-diastolic volume index; EF, ejection fraction; ESVi, end-systolic volume index; GCS, global circumferential strain; GLS, global longitudinal strain; LV, left ventricle; Mi, mass index; RV, right ventricle; SVi, stroke volume index.
*P < 0.05 vs. endurance.
**P < 0.05 vs. power.
***P < 0.05 vs. mixed.

morphology and systolic function and its relation to age, sex, sports classes, and peak exercise capacity. Athlete's heart comprises a significant dilation of both the left and the right ventricle, with males presenting with larger dimensions and lower systolic functional measures. Compared with adolescent athletes, adults had larger LV volumes; on the other hand, RV dimensions did not differ. Concerning biventricular function, resting LV mechanics of the athlete's heart was characterized by a balanced decrease in GLS and GCS, whereas in the right ventricle, the circumferential deformation decreased disproportionately compared with the longitudinal shortening (*Figure 2*). Interestingly, a more pronounced shift towards this mechanical pattern was associated with better exercise capacity. Endurance athletes demonstrated significantly larger RV volumes and decreased resting function compared with the other sports classes.

The athlete's heart has been at the centre of clinical and scientific interest for several decades. Recent increases in the popularity of recreational sports and also in applying exercise as a therapeutic intervention, as well as the emergence of advanced imaging techniques also resulted in a growing number of studies focusing on the basics of cardiac exercise physiology.[9–15] Regular, intense exercise leads to a complex remodelling of cardiac morphology and function in order to further enhance athletic performance. Numerous studies have established the 'conventional' exercise-induced alterations in elite athletes, namely the increased LV volumes and mass, and recently, similar changes were demonstrated concerning the RV as well.[5,16,17] In this study, we have utilized 3D echocardiography, a technique that offers better agreement with gold-standard cardiac magnetic resonance (CMR) imaging compared with conventional M-mode and 2D echocardiographic measurements and confirmed the above-mentioned phenomena.[18] Beyond the exercise regime, other factors, such as age, sex, and the type of sport may impact cardiac remodelling. Although adaptation is generally similar in male and female athletes, previous studies have shown that male athletes have greater absolute cardiac dimensions.[2,16,19] Similarly to these results, male athletes had significantly higher LV and RV volumes and LV mass in our cohort as well. However, it is important to emphasize, that in female athletes all the features of the exercise-induced remodelling are present when compared with sedentary female controls. As anticipated, adult athletes participated in competitive sports for a longer period, thus larger LV volumes and mass could be observed. Still, despite the higher absolute training load of adults, the RV volumes were comparable between adolescent and adult athletes. These findings suggest that the right heart remodelling precedes its left counterpart with significant dilation even at a younger age and especially, in females. Comparing athletes of different sports classes, endurance athletes are often described as having the most extensive but

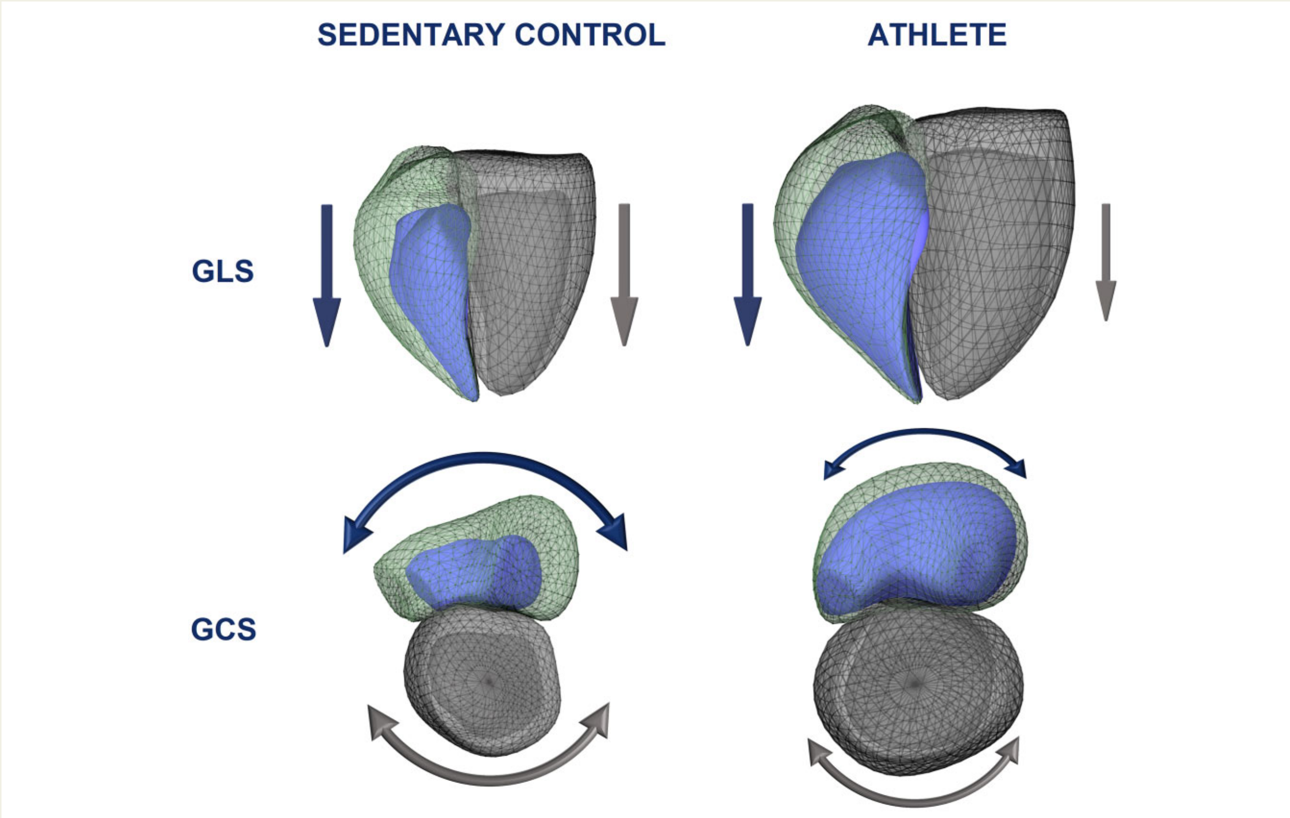


Figure 2 Graphical representation of a healthy, sedentary volunteer, and an elite water polo athlete in terms of three-dimensional left and right ventricular volumes and mechanics. The athlete shows larger left ventricular (228 vs. 143 mL) and right ventricular end-diastolic (237 vs. 139 mL) and end-systolic (left ventricular end-systolic volume: 104 vs. 42 mL; right ventricular end-systolic volume: 118 vs. 47 mL) volumes compared with the sedentary control (light grey mesh—left ventricular end-diastolic volume; dark grey surface—left ventricular end-systolic volume; green mesh—right ventricular end-diastolic volume; blue surface—right ventricular end-systolic volume). Concerning systolic function, left ventricular global longitudinal (-20.3 vs. -23.1%) and global circumferential (-25.8 vs. -33.6%) strain values showed a balanced decrease in the athlete, whereas right ventricular global circumferential strain (-12.6 vs. -28.6%) was disproportionately decreased compared with right ventricular global longitudinal strain (-21.1% vs. -25.2%) in the water polo athlete.

balanced dilation of all four cardiac chambers.[9] A recent publication, however, suggested that the RV undergoes a disproportionate remodelling compared with the LV, which resonates with our findings.[20]

Direct associations between increased biventricular volumes and better athletic performance have been previously reported.[16,21–23] According to this study, LV and RV volumes significantly correlate with peak exercise capacity; however, RV EDVi was found to be the strongest independent predictor among other volumetric or functional parameters. This result also highlights the paramount importance of the RV in determining athletic performance, which remained unrecognized for a long time due to the more challenging evaluation of the RV using conventional echocardiographic parameters.

Concerning the resting systolic function of the athlete's heart, data available in the literature are conflicting. Recent publications have presented results of supernormal/normal as well as reduced resting LV EF values.[10,11,24] Although 3D echocardiographic evaluation offers a promising solution in terms of measurement accuracy, studies are still inconsistent in terms of the features of normal resting ventricular function.[25,26] This might be mainly attributable to the significant heterogeneity of the athlete populations. According to our results derived from our large database of elite athletes, resting values of LV and RV EF were mildly but significantly reduced compared with sedentary controls, which is consistent with our previous findings using smaller cohorts.[5,16,17] This alteration in cardiac function may be explained by the fact, that a less strenuous contraction is required from a larger chamber to maintain a normal stroke volume during resting conditions. Consequently, data are scarce and inconclusive regarding the associations between resting systolic functions and exercise capacity. However, La Gerche *et al.*[22] observed an inverse correlation between LV EF and peak oxygen uptake. Similarly, we showed significant inverse correlations between 3D echocardiography-derived LV and RV EF and VO_2/kg.

Despite the emergence of advanced imaging techniques, studies have still provided inconsistent data ranging from decreased or maintained to even increased resting LV strain values.[25,27,28] Although there is an established increase in the myocardial contractility of the athlete's heart, GLS cannot reflect the contractile state during resting conditions.[29] The above-mentioned geometric adaptation along with the load-dependency of these measures justifies this shortcoming.[1] In parallel with our previous studies, we observed a balanced decrease in resting values of 3D LV GLS and also GCS.[5,16,17] Importantly, the deterioration of LV longitudinal vs. circumferential shortening is often dissociated in different pathological conditions; thus, this balanced decrease may rather point at a physiologic process.[30] Power athletes showed the lowest resting values compared with the other sports classes. This may be explained by the different training profile of these athletes: a mainly static exercise regime imposes significant pressure load on the LV, which manifests in reduced LV deformation. Correlations of decreased LV deformation with higher systolic blood pressure and increased LV mass were previously reported in power athletes.[31,32]

Regarding the RV mechanical pattern, we face a knowledge gap, since RV circumferential shortening has not been thoroughly investigated in the context of the athlete's heart. It has been demonstrated in healthy sedentary individuals that non-longitudinal motion components largely contribute to global RV pump function, nevertheless, they cannot be effectively measured without the use of 3D imaging.[3] In a cohort of water polo athletes, we have previously shown that the relative contribution of longitudinal shortening to global RV EF is supernormal, while non-longitudinal deformation is decreased compared with sedentary controls.[17] This study verifies these findings in a large cohort of athletes showing that the athlete's heart is characterized by a disproportionate decrease in RV GCS compared with RV GLS. Three-dimensional-based RV GLS (along with other measures of RV longitudinal shortening, i.e. TAPSE and 2D longitudinal strain) was similar between athletes and controls in this study. This is particularly interesting since the decrease of LV longitudinal shortening would imply a parallel decrease in RV longitudinal shortening. In pathological conditions (such as left-heart diseases), due to the change in the function of the interventricular septum and myofibre arrangement, such a decrease in LV and subsequent RV longitudinal shortening is compensated with an increase in RV radial (circumferential) shortening.[4] However, in the context of the athlete's heart, circumferential shortening is decreased along with maintained or even supernormal longitudinal shortening, which was also confirmed by a recent meta-analysis.[33] We hypothesize that despite the significant chamber dilation, the myofibre meshwork transitions into a more advantageous (more oblique) orientation that will result in the above-mentioned mechanical pattern. A supernormal RV longitudinal shortening may support right atrial filling by enhancing venous return in systole, which can serve as an advantageous component of cardiac function, especially during exercise. Notably, similar changes in myofibre orientation may be present concerning the LV and its twist and untwist mechanics.[34] Detailed analysis of ventricular deformation can identify characteristic exercise-induced properties of the myocardium that can unfold even during resting conditions. These alterations may support effective systolic and diastolic ventricular function during significant haemodynamic demands arising from intense exercise.

On the other hand, the deterioration of RV circumferential shortening (especially at the basal free wall segments) is an established early marker of pressure overload-induced wall stress in various cardiac pathologies.[35,36] It is also known that during vigorous exercise, the right side of the heart is exposed to a disproportionate increase of afterload, which can potentially manifest in adverse RV remodelling.[37,38] The above-mentioned meta-analysis by Dawkins *et al.*[33] also aimed to describe the influence of long-term exercise on RV region-specific adaptation. Although, they found comparable RV global and free-wall longitudinal strain between athletes and controls, regional strain values were greater at the apex but lower at the RV base in athletes. Whether this lower basal function is just the result of the altered myofibre architecture or secondary to pressure overload during bouts of exercise warrants further investigations. Notably, RV function may be more profoundly affected by endurance training; La Gerche *et al.*[39] demonstrated an acute reduction in RV function after an endurance race. In our cohort, athletes competing in endurance sport disciplines presented with the lowest values of RV EF, RV GLS, and also RV GCS.

Still, we found a significant inverse correlation between RV GCS and peak exercise capacity, moreover, RV GCS was an independent predictor of fitness by multivariable linear regression. Therefore, in the case of the athlete's heart, the worse is the resting ventricular function, the better is the exercise capacity.

Limitations

There are several limitations that have to be acknowledged. First, this is a single-centre, retrospective, cross-sectional study with a limited number of cases. However, the utilization of advanced echocardiographic techniques along with a same-day CPET elevates its value. Although this study enrolled athletes from all four types of sports classes, the distribution of mixed, endurance, power, and skill athletes was imbalanced. Nevertheless, we were able to enroll a large number of female and also adolescent athletes, who are rather underrepresented in contemporary literature. We did not compare our measurements to a gold standard, nevertheless, all the post-processing software are extensively validated against CMR. Atrial volumes were quantified by 2D and not 3D echocardiography as currently no vendor independent 3D solution is available.

Conclusions

In competitive elite athletes, regular, intense physical exercise resulted in significant and specific changes in biventricular morphology and function. Resting LV and RV EFs are lower compared with sedentary controls. Concerning the LV, there is a balanced decrease in longitudinal and circumferential shortening; however, RV circumferential shortening shows a disproportionate decrement. These changes are associated with a better exercise capacity as measured by CPET. Our results emphasize the importance of 3D imaging in the evaluation of the athlete's heart to understand the normal exercise physiology and potentially, to detect adverse remodelling. Further research is warranted to establish the development/regression dynamics of our findings.

Supplementary material

Supplementary material is available at *European Journal of Preventive Cardiology* online.

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References

1. Tokodi M, Oláh A, Fábián A, Lakatos BK, Hizoh I, Ruppert M, Sayour AA, Barta BA, Kiss O, Sydó N, Csulak E, Ladányi Z, Merkely B, Kovács A, Radovits T. Novel insights into the athlete's heart: is myocardial work the new champion of systolic function?. Eur. Heart J. Cardiovasc. Imaging 2022;**23**:188–197.
2. Csecs I, Czimbalmos C, Toth A, Dohy Z, Suhai IF, Szabo L, Kovacs A, Lakatos B, Sydo N, Kheirkhahan M, Peritz D, Kiss O, Merkely B, Vago H. The impact of sex, age and training on biventricular cardiac adaptation in healthy adult and adolescent athletes: cardiac magnetic resonance imaging study. *Eur J Prev Cardiol* 2020;**27**:540–549.
3. Lakatos BK, Nabeshima Y, Tokodi M, Nagata Y, Tősér Z, Otani K, Kitano T, Fábián A, Ujvári A, Boros AM, Merkely B, Kovács A, Takeuchi M. Importance of nonlongitudinal motion components in right ventricular function: three-dimensional echocardiographic study in healthy volunteers. *J Am Soc Echocardiogr* 2020;**33**:995–1005.e1.
4. Surkova E, Kovacs A, Tokodi M, Lakatos BK, Merkely B, Muraru D, Ruocco A, Parati G, Badano LP. Contraction patterns of the right ventricle associated with different degrees of left ventricular systolic dysfunction. *Circ Cardiovasc Imaging* 2021;**14**:e012774.
5. Fábián A, Lakatos BK, Tokodi M, Kiss AR, Sydó N, Csulak E, Kispál E, Babity M, Szűcs A, Kiss O, Merkely B, Kovács A. Geometrical remodeling of the mitral and tricuspid annuli in response to exercise training: a 3-D echocardiographic study in elite athletes. *Am J Physiol Heart Circ Physiol* 2021;**320**:H1774–H1785.
6. Lang RM, Badano LP, Mor-Avi V, Afilalo J, Armstrong A, Ernande L, Flachskampf FA, Foster E, Goldstein SA, Kuznetsova T, Lancellotti P, Muraru D, Picard MH, Rietzschel ER, Rudski L, Spencer KT, Tsang W, Voigt JU. Recommendations for cardiac chamber quantification by echocardiography in adults: an update from the American Society of Echocardiography and the European Association of Cardiovascular Imaging. *J Am Soc Echocardiogr* 2015;**28**:1–39.e14.
7. Tokodi M, Staub L, Budai Á, Lakatos BK, Csákvári M, Suhai FI, Szabó L, Fábián A, Vágó H, Tősér Z, Merkely B, Kovács A. Partitioning the right ventricle into 15 segments and decomposing its motion using 3D echocardiography-based models: the updated ReVISION method. *Front Cardiovasc Med* 2021;**8**:622118.
8. Pelliccia A, Caselli S, Sharma S, Basso C, Bax JJ, Corrado D, D'Andrea A, D'Ascenzi F, Di Paolo FM, Edvardsen T, Gati S, Galderisi M, Heidbuchel H, Nchimi A, Nieman K, Papadakis M, Pisicchio C, Schmied C, Popescu BA, Habib G, Grobbee D, Lancellotti P; European Association of Preventive Cardiology (EAPC) and European Association of Cardiovascular Imaging (EACVI). European Association of Preventive Cardiology (EAPC) and European Association of Cardiovascular Imaging (EACVI) joint position statement: recommendations for the indication and interpretation of cardiovascular imaging in the evaluation of the athlete's heart. *Eur Heart J* 2018;**39**:1949–1969.
9. Scharhag J, Schneider G, Urhausen A, Rochette V, Kramann B, Kindermann W. Athlete's heart: right and left ventricular mass and function in male endurance athletes and untrained individuals determined by magnetic resonance imaging. *J Am Coll Cardiol* 2002;**40**:1856–1863.
10. Baggish AL, Wood MJ. Athlete's heart and cardiovascular care of the athlete: scientific and clinical update. *Circulation* 2011;**123**:2723–2735.
11. Prior DL, La Gerche A. The athlete's heart. *Heart* 2012;**98**:947–955.
12. Utomi V, Oxborough D, Whyte GP, Somauroo J, Sharma S, Shave R, Atkinson G, George K. 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**:1727–1733.
13. Dawes TJ, Corden B, Cotter S, de Marvao A, Walsh R, Ware JS, Cook SA, O'Regan DP. Moderate physical activity in healthy adults is associated with cardiac remodeling. *Circ Cardiovasc Imaging* 2016;**9**:e004712.
14. D'Ascenzi F, Anselmi F, Piu P, Fiorentini C, Carbone SF, Volterrani L, Focardi M, Bonifazi M, Mondillo S. Cardiac magnetic resonance normal reference values of biventricular size and function in male athlete's heart. *JACC Cardiovasc Imaging* 2019;**12**:1755–1765.
15. Cattadori G, Segurini C, Picozzi A, Padeletti L, Anza C. Exercise and heart failure: an update. *ESC Heart Fail* 2018;**5**:222–232.
16. Lakatos BK, Molnar AA, Kiss O, Sydo N, Tokodi M, Solymossi B, Fabian A, Dohy Z, Vago H, Babity M, Bognar C, Kovacs A, Merkely B. Relationship between cardiac remodeling and exercise capacity in elite athletes: incremental value of left atrial morphology and function assessed by three-dimensional echocardiography. *J Am Soc Echocardiogr* 2020;**33**:101–109.e1.
17. Lakatos BK, Kiss O, Tokodi M, Tősér Z, Sydó N, Merkely G, Babity M, Szilágyi M, Komócsin Z, Bognár C, Kovács A, Merkely B. Exercise-induced shift in right ventricular contraction pattern: novel marker of athlete's heart? *Am J Physiol Heart Circ Physiol* 2018;**315**:H1640–H1648.
18. Maffessanti F, Muraru D, Esposito R, Gripari P, Ermacora D, Santoro C, Tamborini G, Galderisi M, Pepi M, Badano LP. Age-, body size-, and sex-specific reference values for right ventricular volumes and ejection fraction by three-dimensional echocardiography: a multicenter echocardiographic study in 507 healthy volunteers. *Circ Cardiovasc Imaging* 2013;**6**:700–710.
19. Sun B, Ma JZ, Yong YH, Lv YY. The upper limit of physiological cardiac hypertrophy in elite male and female athletes in China. *Eur J Appl Physiol* 2007;**101**: 457–463.
20. La Gerche A, Heidbuchel H, Burns AT, Mooney DJ, Taylor AJ, Pfluger HB, Inder WJ, Macisaac AI, Prior DL. Disproportionate exercise load and remodeling of the athlete's right ventricle. *Med Sci Sports Exerc* 2011;**43**:974–981.
21. Steding K, Engblom H, Buhre T, Carlsson M, Mosen H, Wohlfart B, Arheden H. Relation between cardiac dimensions and peak oxygen uptake. *J Cardiovasc Magn Reson* 2010;**12**:8.
22. La Gerche A, Burns AT, Taylor AJ, Macisaac AI, Heidbuchel H, Prior DL. Maximal oxygen consumption is best predicted by measures of cardiac size rather than function in healthy adults. *Eur J Appl Physiol* 2012;**112**:2139–2147.
23. Bernardino G, Sanz de la Garza M, Domenech-Ximenos B, Prat-Gonzàlez S, Perea RJ, Blanco I, Burgos F, Sepulveda-Martinez A, Rodriguez-Lopez M, Crispi F, Butakoff C, González Ballester MA, De Craene M, Sitges M, Bijnens B. Three-dimensional regional bi-ventricular shape remodeling is associated with exercise capacity in endurance athletes. *Eur J Appl Physiol* 2020;**120**:1227–1235.
24. Abergel E, Chatellier G, Hagege AA, Oblak A, Linhart A, Ducardonnet A, Menard J. Serial left ventricular adaptations in world-class professional cyclists: implications for disease screening and follow-up. *J Am Coll Cardiol* 2004;**44**: 144–149.
25. Lo Iudice F, Petitto M, Ferrone M, Esposito R, Vaccaro A, Buonauro A, D'Andrea A, Trimarco B, Galderisi M. Determinants of myocardial mechanics in top-level endurance athletes: three-dimensional speckle tracking evaluation. *Eur Heart J Cardiovasc Imaging* 2017;**18**:549–555.
26. Bjerring AW, Landgraff HE, Leirstein S, Aaeng A, Ansari HZ, Saberniak J, Murbræch K, Bruun H, Stokke TM, Haugaa KH, Hallén J, Edvardsen T, Sarvari SI. Morphological changes and myocardial function assessed by traditional and novel echocardiographic methods in preadolescent athlete's heart. *Eur J Prev Cardiol* 2018;**25**:1000–1007.
27. D'Ascenzi F, Caselli S, Solari M, Pelliccia A, Cameli M, Focardi M, Padeletti M, Corrado D, Bonifazi M, Mondillo S. Novel echocardiographic techniques for the evaluation of athletes' heart: a focus on speckle-tracking echocardiography. *Eur J Prev Cardiol* 2016;**23**:437–446.
28. Beaumont A, Grace F, Richards J, Hough J, Oxborough D, Sculthorpe N. Left ventricular speckle tracking-derived cardiac strain and cardiac twist mechanics in athletes: a systematic review and meta-analysis of controlled studies. *Sports Med* 2017;**47**:1145–1170.
29. Olah A, Kovacs A, Lux A, Tokodi M, Braun S, Lakatos BK, Matyas C, Kellermayer D, Ruppert M, Sayour AA, Barta BA, Merkely B, Radovits T. Characterization of the dynamic changes in left ventricular morphology and function induced by exercise training and detraining. *Int J Cardiol* 2019;**277**:178–185.
30. Szelényi Z, Fazakas Á, Szénási G, Tegze N, Fekete B, Molvarec A, Hadusfalvy-Sudár S, Jánosi O, Kiss M, Karádi I, Vereckei A. The mechanism of reduced longitudinal left ventricular systolic function in hypertensive patients with normal ejection fraction. *J Hypertens* 2015;**33**:1962–1969; discussion 1969.

31. Szauder I, Kovacs A, Pavlik G. Comparison of left ventricular mechanics in runners versus bodybuilders using speckle tracking echocardiography. *Cardiovasc Ultrasound* 2015;**13**:7.
32. Doronina A, Edes IF, Ujvari A, Kantor Z, Lakatos BK, Tokodi M, Sydo N, Kiss O, Abramov A, Kovacs A, Merkely B. The female athlete's heart: comparison of cardiac changes induced by different types of exercise training using 3D echocardiography. *Biomed Res Int* 2018;**2018**:1–7.
33. Dawkins TG, Curry BA, Wright SP, Meah VL, Yousef Z, Eves ND, Shave RE, Stembridge M. Right ventricular function and region-specific adaptation in athletes engaged in high-dynamic sports: a meta-analysis. *Circ Cardiovasc Imaging* 2021;**14**:e012315.
34. Kovacs A, Apor A, Nagy A, Vago H, Toth A, Nagy AI, Kovats T, Sax B, Szeplaki G, Becker D, Merkely B. Left ventricular untwisting in athlete's heart: key role in early diastolic filling? *Int J Sports Med* 2013;**35**:259–264.
35. Moceri P, Duchateau N, Baudouy D, Schouver ED, Leroy S, Squara F, Ferrari E, Sermesant M. Three-dimensional right-ventricular regional deformation and survival in pulmonary hypertension. *Eur Heart J Cardiovasc Imaging* 2018;**19**:450–458.
36. Bidviene J, Muraru D, Maffessanti F, Ereminiene E, Kovacs A, Lakatos B, Vaskelyte JJ, Zaliunas R, Surkova E, Parati G, Badano LP. Regional shape, global function and mechanics in right ventricular volume and pressure overload conditions: a three-dimensional echocardiography study. *Int J Cardiovasc Imaging* 2021;**37**:1289–1299.
37. La Gerche A, Rakhit DJ, Claessen G. Exercise and the right ventricle: a potential Achilles' heel. *Cardiovasc Res* 2017;**113**:1499–1508.
38. Sanz-de la Garza M, Carro A, Caselli S. How to interpret right ventricular remodeling in athletes. *Clin Cardiol* 2020;**43**:843–851.
39. La Gerche A, Burns AT, Mooney DJ, Inder WJ, Taylor AJ, Bogaert J, Macisaac AI, Heidbuchel H, Prior DL. Exercise-induced right ventricular dysfunction and structural remodelling in endurance athletes. *Eur Heart J* 2012;**33**:998–1006.