

Est.
1841

YORK
ST JOHN
UNIVERSITY

Beaumont, Alexander ORCID

logoORCID: <https://orcid.org/0000-0002-5773-6356>, Oxborough, David, George, Keith, Rowland, Thomas, Sculthorpe, Nicholas, Lord, Rachel and Unnithan, Viswanath (2020) Superior cardiac mechanics without structural adaptations in pre-adolescent soccer players. *European Journal of Preventive Cardiology*, 27 (14). pp. 1494-1501.

Downloaded from: <https://ray.yorks.ac.uk/id/eprint/4171/>

The version presented here may differ from the published version or version of record. If you intend to cite from the work you are advised to consult the publisher's version:

<https://journals.sagepub.com/doi/full/10.1177/2047487319890177>

Research at York St John (RaY) is an institutional repository. It supports the principles of open access by making the research outputs of the University available in digital form. Copyright of the items stored in RaY reside with the authors and/or other copyright owners. Users may access full text items free of charge, and may download a copy for private study or non-commercial research. For further reuse terms, see licence terms governing individual outputs. [Institutional Repository Policy Statement](#)

RaY

Research at the University of York St John

For more information please contact RaY at ray@yorks.ac.uk

1 **Superior cardiac mechanics without structural adaptations in pre-adolescent soccer players**

2

3 Alexander Beaumont ^a, David Oxborough ^c, Keith George ^c, Thomas. W. Rowland ^b, Nicholas

4 Sculthorpe ^b, Rachel Lord ^d, Viswanath. B. Unnithan ^{b,*}

5

6 ^a School of Sport, York St John University, York, UK; ^b Institute of Clinical Exercise and Health

7 Science, School of Health and Life Sciences, University of the West of Scotland, Hamilton, Scotland;

8 ^c Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, Liverpool,

9 UK; ^dCardiff Centre for Exercise and Health, Cardiff Metropolitan University, Cardiff, UK.

10

11 * Corresponding author:

12 Professor V.B. Unnithan, Ph.D., FACSM

13 Institute of Clinical Exercise and Health Science

14 School of Health and Life Sciences

15 University of the West of Scotland

16 Hamilton

17 Scotland, UK

18 Tel: 01698 894413

19 E-mail: vish.unnithan@uws.ac.uk

20

21

22 Word count: 4245

23

24

25 **Abstract**

26

27 **Aims:** This study aimed to evaluate left ventricular (LV) structure, function and mechanics, in highly-
28 trained, pre-adolescent soccer players (SP) compared to age- and sex-matched controls (CON).

29 *Design:* The study design was a prospective, cross-sectional comparison of LV structure, function and
30 mechanics.

31 **Methods:** Twenty-two male SP from two professional youth soccer academies (age: 12.0±0.3 years)
32 and twenty-two recreationally active CON (age: 11.7±0.3 years) were recruited. Two-dimensional
33 conventional and speckle tracking echocardiography were used to quantify LV structure, function and
34 peak/temporal values for LV strain and twist, respectively.

35 **Results:** End-diastolic volume index was larger in SP ($51 \pm 8 \text{ mm}/(\text{m}^2)^{1.5}$ vs. $45 \pm 6 \text{ mm}/(\text{m}^2)^{1.5}$;
36 $p=0.007$) and concentricity was lower in SP ($4.3 \pm 0.7 \text{ g}/(\text{mL})^{0.667}$ vs. $4.9 \pm 1.0 \text{ g}/(\text{mL})^{0.667}$; $p=0.017$),
37 without differences in mean wall thickness between groups ($6.0 \pm 0.4 \text{ mm}$ vs. $6.1 \pm 0.5 \text{ mm}$; $p=0.754$).
38 Peak circumferential strain at the base ($-22.2 \pm 2.5\%$ vs. $-20.5 \pm 2.5\%$; $p=0.029$) and papillary muscle
39 levels ($-20.1 \pm 1.5\%$ vs. $-18.3 \pm 2.5\%$; $p=0.007$) were greater in SP. Peak LV twist was larger in SP
40 ($16.92 \pm 7.55^\circ$ vs. $12.34 \pm 4.99^\circ$; $p=0.035$) and longitudinal early diastolic strain rate was greater in SP
41 ($2.22 \pm 0.40 \text{ s}^{-1}$ vs. $2.02 \pm 0.46 \text{ s}^{-1}$; $p=0.025$).

42 **Conclusions:** Highly-trained SP demonstrated augmented cardiac mechanics with greater
43 circumferential strains, twist and faster diastolic lengthening in the absence of differences in wall
44 thickness between SP and CON.

45

46 **Keywords:** Strain; Echocardiography; Speckle; Youth; Function; Left Ventricle

47

48 **Abstract Word count: 234**

49

50

51

52

53

54 **Introduction**

55 The match-play and training characteristics of soccer^{1,2} presents an ecologically valid model to study
56 the effects of systematic high intensity intermittent exercise training on cardiac structure and function
57 in young, athletes.

58 A recent meta-analysis, has reported larger left ventricular (LV) diameter and wall thickness
59 yet similar conventionally derived indices of systolic and diastolic cardiac function in adolescent
60 athletes compared with non-athletes.³ Additionally, cardiac enlargement increased with chronological
61 age suggesting a potential role of hormones in pubertal adaptation. Importantly, the influence of
62 exercise training on cardiac structure and function in pre-adolescent athletes may be ascertained without
63 the confounding factors of growth and maturation. However, the effects of soccer training in these
64 younger athletes are less clear, with some studies reporting similar absolute and scaled wall thicknesses
65 between pre-adolescent athletes and controls.⁴⁻⁶

66 Our group recently documented LV structure and function in highly-trained pre-adolescent
67 athletes, with a particular focus on conventional indices of LV function.⁷ Speckle tracking
68 echocardiography (STE) comprehensively assesses LV mechanics by quantifying deformation in the
69 longitudinal, circumferential and radial planes, as well as rotation and twist.^{8,9} Studies using STE to
70 compare young athletes with age-matched controls have been conflicting,¹⁰⁻¹² likely due to variations
71 in maturity status, the sex of the athletes, and disparate sports being studied. Some however, have
72 reported lower longitudinal strain¹² and augmented twist.¹³ Thus, there is a paucity of data detailing LV
73 mechanics in pre-adolescent SP which warrants further investigation. Assessment of myocardial strains
74 using STE will further our understanding on the coupling between LV structure and function in this
75 population. Additionally, STE can facilitate temporal mechanical data that will extend our
76 understanding of strains and rotations throughout the cardiac cycle.

77 Taken together, with the increased professionalization and subsequent increased training loads
78 in elite youth soccer, at very early ages, there is a need to further interrogate global and regional markers
79 of LV structure, function and mechanics. It was hypothesised that, (1) LV structure would not differ

80 between pre-adolescent SP and controls (CON); (2) LV longitudinal strain would be lower in SP
81 compared to CON, while, (3) LV twist mechanics would be greater in SP than CON.

82 **Methods**

83 *Participants*

84 Twenty-two highly trained male youth soccer players (SP, age: 12.0 ± 0.3 years) and 22 recreationally
85 active males (CON, mean age: 11.7 ± 0.3 years) were recruited to the study. Two of the SP were British
86 African-Caribbean with the remainder Caucasian. Similarly, one of the CON was of British African-
87 Caribbean origin and the remainder were Caucasian.

88 The SP training profiles were as follows: 4.5 ± 1.5 years training, 11 ± 1 months per year
89 training, 4 ± 1 training sessions per week and 9.4 ± 2.4 hours per week of training. This volume of
90 exercise training had been consistent for the entirety of their active training years. SP played one
91 competitive match per week and had been engaged in competitive soccer matches for 4 ± 2 years. The
92 SP were recruited from two Category one English Premier league youth soccer academies. For one
93 club, 14 boys from the U12 squad and their parents were approached, of which 3 were not enrolled
94 because of either personal circumstances ($n=2$) or a football related injury ($n=1$). At the second club,
95 researchers provided information to 15 U12 players and their parents, of which 2 were recovering from
96 injury, 1 was released from the club after signing up from the study, and 1 signed up and simply did not
97 attend the testing. Accordingly, all recruitment was consecutive and included 11 participants from both
98 clubs, with a total of 22 SP. CON participants took part in compulsory physical education of 2 hours
99 per week (the same as SP), were all recreationally active and without engagement of systematic training.
100 The CON self-reported 1.53 ± 1.77 hours per week of physical activity.

101 Written informed parental and participant consent was obtained prior to participation. All
102 procedures performed in the study were in accordance with the Declaration of Helsinki and the study
103 was reviewed and approved by Staffordshire University Ethics Committee.

104

105 *Protocol/Measurements*

106 Participants were asked to refrain from physical activity for 12 hours prior to the visit. Physical activity
107 and training questionnaires¹⁴ were completed prior to the testing. Following this, stature and body mass

108 were measured. Maturity status was quantified using maturity offset.^{7,15} Resting arterial blood pressure
109 was recorded in the left arm by an automated blood pressure cuff (Boso, Medicus, Jungingen,
110 Germany) and heart rate was assessed by a 12-lead electrocardiogram (ECG) (CardioExpress SL6,
111 Spacelabs Healthcare, Washington US). No abnormalities were detected from the ECG recordings in
112 the participants included within the final analysis. Resting echocardiographic measurements were taken
113 in the left lateral decubitus position. Body surface area (BSA) was calculated by Mosteller formula.¹⁶

114

115 *Two-dimensional echocardiography*

116 2D echocardiographic procedures were performed by two sonographers (soccer players [DO] and
117 controls [DO + RL]) using a commercially available ultrasound system (VividQ Ultrasound System,
118 GE Ltd, Horton, Norway) and images were analysed offline (EchoPac version 6.0, GE Ltd, Horton,
119 Norway). Conventional measurements of resting LV dimensions and volumes (LV end-diastolic
120 dimension [LVEDd], LV end-systolic dimension [LVESd], LV end-diastolic volume [LVEDV], LV
121 end-systolic volume [LVESV]) and the subsequent calculations of LV mass and relative wall thickness
122 (RWT) were made in accordance with American Society of Echocardiography (ASE) guidelines¹⁷ and
123 have been reported previously.⁷ Linear LV dimensions were scaled to $BSA^{0.5}$, LV mass to height^{2.7} and
124 volumes to $BSA^{1.5}$.¹⁸ Concentricity was calculated as LVM divided by allometrically scaled LVEDV
125 ($LVEDV^{0.667}$).¹⁹ Sphericity index was calculated as LV length divided by LVEDd.²⁰

126 Peak mitral inflow velocities and pulsed wave tissue Doppler imaging (TDI) were assessed as
127 previously reported.⁷ E/E' was calculated as an estimate of LV filling pressure²¹ from the average of
128 septal and lateral E'.

129 Stroke volume (SV) and ejection fraction (EF) were calculated using Simpson's biplane method
130 with cardiac output (Q) was determined by multiplying SV by the ECG determined heart rate (HR).
131 Both Q and SV were adjusted for BSA (Qindex and SVindex).

132 LV mechanics were determined from 2D images with frame rates maintained as high as
133 possible within the range of 40 to 90 fps. The cardiac cycle with the most defined endocardial border
134 was used for analysis. Adjustments in frequency and gain were used to optimise endocardial
135 delineation, with a single focal zone placed mid LV cavity to reduce the impact of beam divergence.

136 Aortic valve closure (AVC) was identified from the pulsed wave Doppler of LVOT flow and used to
137 signify end systole. Offline analysis using dedicated speckle tracking software (Echopac V6.0, GE
138 Healthcare, Horton, Norway) provided assessment of LV strains, strain rate (SR), rotations and net
139 twisting.

140 Longitudinal strain was determined using the apical 4-chamber view. Global values were
141 calculated as an average of 6 myocardial segments from the basal, mid and apical septum and lateral
142 walls. Circumferential and radial strains were determined from the segmental average at the basal and
143 mid-papillary levels. Using the mitral valve and apical levels, LV rotations were determined and twist
144 was calculated as the difference between clockwise basal and counter-clockwise apical rotations during
145 systole. In all instances, peak values and temporal analyses were obtained by importing stored traces
146 into a Spreadsheet (Microsoft Corporation, Washington, USA) with a cubic spline add-in (SRS1
147 software, Boston, USA). Data were normalised to 5% increments during systole and diastole. Good
148 reliability of LV mechanics data has also been established by this research team.⁹

149

150 *Statistical analysis*

151 Normality of data was assessed using Shapiro-Wilk. For normally distributed data, a Student's
152 independent t-test was used to compare LV structure, function and mechanics in SP and CON. For non-
153 normally distributed data, a Mann-Whitney U test was employed. The same procedures were used for
154 temporal analysis at each 5% increment independently. A sample size of 22 SP provided a (1- β) of 80%
155 at an alpha level of 0.05. Statistical significance was granted at $p < 0.05$. Statistical analyses were
156 performed using jamovi (version 0.9).²²

157

158 **Results**

159 *Missing data*

160 Data were not obtained in CON (n=1) due to poor image quality in indices derived from Simpson's
161 Biplane. Tissue Doppler and longitudinal strain indices were absent for CON (n=1). Due to >2 segments

162 excluded due to poor tracking in the apical plane, LV twist mechanics were not available for SP (n=1)
163 and CON (n= 4).

164

165 *Physical characteristics*

166 SP were chronologically slightly older ($p < 0.05$) than CON (12.0 ± 0.3 and 11.7 ± 0.3 years), but
167 maturity offset (-2.1 ± 0.6 and -2.1 ± 0.6 years) and age at peak height velocity (14.0 ± 0.5 and $13.9 \pm$
168 0.6 years) were similar between SP and CON, (both $p > 0.05$). Similarly, stature (1.51 ± 0.06 and $1.49 \pm$
169 0.07 m) and body mass (40.2 ± 5.8 and 44.0 ± 11.7 kg) were similar between SP and CON, respectively
170 (both $p > 0.05$). There were no inter- group differences for systolic (SP: 100 ± 8 mmHg; CON: 105 ± 13
171 mmHg) and diastolic blood pressure (SP: 61 ± 9 mmHg; CON: 61 ± 10 mmHg).

172

173 *Conventional LV structure and function*

174 Absolute and scaled SV, as well as scaled LVEDV were greater in SP than CON (all $p < 0.05$). Absolute
175 LV diameters, mean wall thickness and mass were not different between SP and CON (all $p > 0.05$),
176 whereas concentricity was lower and sphericity index greater in SP than CON, respectively (all $p <$
177 0.05 , Table 1).

178 Conventionally derived systolic and diastolic function in SP and CON are presented in
179 Appendix Table A.1. LV EF was greater in SP than CON, whereas absolute and scaled lateral S' were
180 lower in SP (all $p < 0.05$). E wave deceleration time was longer in SP than CON ($p < 0.05$). No other
181 functional differences were observed between groups.

182

183 **[Table 1]**

184

185 *LV mechanics*

186 Peak longitudinal strain was not different between groups ($p > 0.05$). Circumferential strain at the basal
187 and papillary muscle levels were greater in SP than CON (both $p < 0.05$). Also, peak circumferential and
188 longitudinal diastolic SR were greater in SP than CON (both $p < 0.05$). Apical rotation was higher in SP
189 than CON ($p < 0.05$), without differences at the basal level ($p > 0.05$) and thus, peak LV twist was greater

190 in SP ($p<0.05$). No further differences in peak LV mechanics were observed between groups (all
191 $p>0.05$, Table 2).

192 In SP, longitudinal SR was greater than CON during early diastole ($p<0.05$) and showed a
193 leftward shift in the descending arm during mid diastole (Fig. 1 A, B). Circumferential strain at basal
194 and papillary muscle levels were greater in SP than CON throughout systole ($p<0.05$). SR at the
195 papillary muscle level was greater in SP ($p<0.05$), corresponding to early diastole (Appendix Fig. B.1).
196 Similarly, apical rotation and twist were greater in SP than CON through the majority of systole
197 ($p<0.05$), while temporal analysis of basal rotation did not differ between groups ($p>0.05$, Appendix
198 Fig. B.2).

199 [Table 2]

200 [Fig. 1]

201 Discussion

202 The major findings from the study were that SP had augmented peak LV mechanics (circumferential
203 strain, apical rotation and twist) and faster early diastolic lengthening. Additionally, SP had lower
204 concentricity than CON, without concomitant differences in wall thickness or longitudinal strain
205 between SP and CON.

206 Lower concentricity was evident in the presence of larger scaled LVEDV, indicative of
207 heightened preload, in SP compared to CON. It is possible that this is the consequence of plasma volume
208 expansion common in well trained adolescents.²³ The similar LV structure between groups contradicts
209 previous echocardiographic work that has reported greater LV wall thickness or chamber diameter in
210 pre-adolescent SP.^{12,24} These contrasting findings may be a product of differences in maturation status
211 of the studied populations. Indeed, a recent meta-analysis found pre-adolescent athletes (<14 years)
212 presented cardiac enlargement to a lesser extent than those within the pubertal growth stage.³ Further,
213 Nottin et al⁴ found similar wall thicknesses in pre-pubertal cyclists and sedentary children. Taken
214 together, these data support the contention that sufficient maturity is necessary to promote exercise
215 induced increases in LV structure.

216 Similar longitudinal strain between SP and CON disagrees with a similar study in young
217 footballers,¹² yet supports the majority of existing literature in young athletes.^{10,11} Although

218 documentation of longitudinal strain in paediatric athletes is currently in its infancy, these observations
219 corroborate with the adult athlete's heart that longitudinal strain remains largely unaltered in chronically
220 trained athletes.²⁵ Reduced longitudinal strain has been suggested as an uncommon feature of the adult
221 athlete's heart²⁶ and this may hold true also for paediatric athletes given the accumulation of evidence
222 to suggest unaltered longitudinal strain in healthy athletic children.

223 Circumferential strain was greater in SP at both the base and papillary muscle levels and
224 highlights a more notable difference in systolic functioning in SP compared to the untrained state.
225 Although the greater circumferential strain in SP contrasts recent work,¹¹ the increase observed here is
226 likely indicative of greater overall systolic function in SP. Yet, the purpose of these adaptations and
227 responsible mechanistic underpinning requires clarification.

228 LV twist was higher in SP mediated through greater apical rotation, without changes in basal
229 rotation, with temporal analysis indicating higher apical rotation and twist through the majority of
230 systole. To our knowledge, this is the first echocardiographic documentation of LV twist mechanics in
231 pre-adolescent athletes, yet concurs with a recent MRI study.¹³ These data begin to define the twisting
232 profiles of chronically trained pre-adolescents, which appear to contrast their elite level adult
233 counterparts of reduced net twist compared to untrained controls.^{25,27} A phasic response in LV twist has
234 been reported in adults with twist increased initially before returning to baseline following structural
235 (true eccentric) remodelling during a more extended period of exercise training.²⁸ Indeed, larger wall
236 thickness appears to drive the reduction in apical rotation and net twist in adults.²⁷ The absence of
237 differences in MWT between SP and CON, could explain why twist was higher in SP, owing to
238 heightened scaled LVEDV, considering the preload dependence of LV apical rotation and twist.²⁹ Thus,
239 the adaptations in chronically trained pre-adolescents may be more reflective of the acute phase of
240 exercise training in adults.²⁸

241 Alternatively, in adults LV twist is influenced by muscle fibre orientation and both apical
242 rotation and twist are independently associated, in a parabolic manner, with sphericity index.²⁰ In this
243 study, sphericity index was slightly higher in SP and may therefore, be placed higher on the ascending
244 arm of the parabolic curve. Irrespective of the mechanistic underpinning, taking these observations

245 together we propose that the heart of paediatric athletes presents a useful model to study the influence
246 of exercise training on LV twist mechanics prior to structural remodelling.

247 Greater circumferential strains and LV twist mechanics could explain the greater EF in pre-
248 adolescent SP. Subsequently, the likely combination of a larger LVEDV and increased EF led to a
249 greater SV. The higher EF observed is not in agreement with other similar work, although the dataset
250 presented within this recent meta-analysis was highly heterogeneous.³ The reasons for discrepancies
251 between studies is unclear. However, EF is considered a surrogate marker of LV pump function,³⁰ and
252 others have reported pre-adolescent athletes have similar EF with comparable or lower LV strain
253 mechanics than CON.¹⁰⁻¹² Whereas, in this study SP had a greater EF which was accompanied with
254 augmented circumferential strain and twist, and thus the altered mechanics may explain the greater EF.
255 Together, the combination of LV mechanics and EF in this study suggests augmented systolic function,
256 yet the functional capacity and potential reserve during exercise warrants further investigation.

257 Mitral inflow and early diastolic tissue velocities were similar between SP and CON, whereas
258 assessment of temporal SR indicated SP had faster diastolic lengthening during the early phases of
259 diastole. SR was lower in SP at 35-40% diastole during the cardiac cycle signifying superior lengthening
260 velocities leading to a longer period of diastasis. These data are supported by the greater peak
261 longitudinal and circumferential (papillary muscle level) SRE in SP than CON. Accordingly, it is
262 plausible that novel assessment using STE may facilitate the detection of subtle differences that are not
263 apparent using TDI, with the former being advantageous in being relatively angle independent and less
264 affected by tethering from adjacent segments.⁸ Collectively, these data suggest improved relaxation
265 may contribute to the enhanced preload/LVEDV and the larger ensuing SV. The functional importance
266 of these observations is yet to be fully realised, however, it is possible that this becomes pertinent to
267 support LV filling especially when diastole shortens during exercise.

268 Considering that youth SP perform at high intensities,^{1,11} the differentiation between
269 pathological and physiological adaptation is of paramount importance and is of current interest.³¹ The
270 present study highlights that elite-level soccer training may be a strong enough stimulus to induce LV
271 mechanical adaptations, even in the absence of morphological difference. We report normal values of
272 LV mechanics in asymptomatic pre-adolescents, therefore, the clinical inference is challenging and may

273 warrant further investigation in those with and without known cardiovascular diseases. Additionally,
274 given the small sample sizes in this study, the clinical implications of this work require further study in
275 larger groups, in association with exercise training status. Future longitudinal data is needed to track
276 these players throughout the volatile growth periods, and as a result, these insights may be helpful to
277 diagnose early stages of cardiomyopathies, such as in HCMP phenotype negative but genotype positive
278 individual, for example.

279 ***Limitations***

280 We acknowledge the limitations of cross-sectional studies including for example, the ability to clearly
281 attribute the cardiac functional changes to soccer training, or the genetic predisposition for
282 preadolescents to perform soccer at a high-level. Plasma volume was not assessed in this study due to
283 ethical restrictions for blood sampling in the studied population. Two-dimensional echocardiography is
284 inherently limited by out-of-plane motion such that, apical and basal imaging planes may not be the
285 same through the entire cardiac cycle.⁸ Limitations in current echocardiographic techniques may
286 explain why LV twist was not obtained in 5 participants (n=1 SP and n=4 CON), since optimal
287 acquisition and speckle-tracking are required at both the base and apex. Accordingly, this resulting in
288 slightly unequal samples sizes between SP and CON. While this presents challenges for clinical utility,
289 these parameters are increasingly acknowledged for their potential use in characterising the athlete's heart,
290 although work is still needed for normative values in LV twist and circumferential strain.³² In this study,
291 however, we applied stringent criteria to both image acquisition and analysis to facilitate confidence in
292 obtaining physiologically meaningful data. Finally, if age-associated increases in LV twist during
293 childhood are related to maturational adaptive modulation^{33,34}, it would be unlikely that the small
294 differences in chronological age between SP and CON would impact results, since biological age
295 (maturity offset) and LV length were similar (i.e. twisting occurs along the same length LV).

296

297 ***Conclusions***

298 Augmented resting LV mechanics (twist, apical rotation and circumferential strain) were observed in
299 highly trained SP, including increased circumferential strains, apical rotation and LV twist, with
300 supportive temporal analysis demonstrating faster early diastolic lengthening than untrained, matched

301 controls. These data highlight superior function derived by STE LV mechanics in the absence of LV
302 wall thickness changes yet with lower concentricity.

303

304

305

306 **Acknowledgments**

307 The authors would like to thank Mr. Marc Campbell (Wolverhampton Wanderers FC) and Dr. Russ
308 Wrigley (Blackburn Rovers FC) in the organisation of the SP data collection sessions. Ms. Katie Davis
309 and Ms. Leanne Brittle for their help with the organisation of the testing session of CON (Staffordshire
310 University Academy).

311

312 **Funding**

313 This research did not receive any specific grant from any funding agency in the public, commercial, or
314 not-for-profit sectors.

315

316 **Declaration of conflicting interests**

317 The Authors declare that there is no conflict of interest.

318

319 **Author contributions statement**

320 V.B.U. conceived and designed the research study. V.B.U., T.W.R., R.L., and D.O. conducted
321 the experiments and collected the data. D.O., and A.B. analysed data. A.B., D.O., N.S., and
322 V.B.U. interpreted the data. A.B. prepared figures and wrote the manuscript. D.O., K.G.,
323 T.W.R., N.S., R.L., and V.B.U. edited and revised the manuscript. All authors read and
324 approved the final version of the manuscript.

325

326 **References**

- 327 1. Wrigley R, Drust B, Stratton G, et al. Quantification of the typical weekly in-season
328 training load in elite junior soccer players. *J Sports Sci* 2012; 30: 1573–1580.
- 329 2. Harley JA, Barnes CA, Portas M, et al. Motion analysis of match-play in elite U12 to U16
330 age-group soccer players. *J Sports Sci* 2010; 28: 1391–1397.
- 331 3. McClean G, Riding NR, Ardern CL, et al. Electrical and structural adaptations of the
332 paediatric athlete’s heart: a systematic review with meta-analysis. *Br J Sports Med*
333 2017; bjsports-2016-097052.
- 334 4. Nottin S, Nguyen LD, Terbah M, et al. Left ventricular function in endurance-trained
335 children by tissue Doppler imaging. *Med Sci Sports Exerc* 2004; 36: 1507–1513.
- 336 5. Rowland TW, Unnithan VB, MacFarlane NG, et al. Clinical manifestations of the
337 ‘athlete’s heart’ in prepubertal male runners. *Int J Sports Med* 1994; 15: 515–519.
- 338 6. Rowland T, Wehnert M, Miller K. Cardiac responses to exercise in competitive child
339 cyclists. *Med Sci Sports Exerc* 2000; 32: 747–752.
- 340 7. Unnithan VB, Rowland TW, George K, et al. Left ventricular function during exercise in
341 trained pre-adolescent soccer players. *Scand J Med Sci Sports*. Epub ahead of print 3
342 July 2018. DOI: 10.1111/sms.13258.
- 343 8. Mor-Avi V, Lang RM, Badano LP, et al. Current and Evolving Echocardiographic
344 Techniques for the Quantitative Evaluation of Cardiac Mechanics: ASE/EAE Consensus
345 Statement on Methodology and Indications Endorsed by the Japanese Society of
346 Echocardiography. *Eur J Echocardiogr* 2011; 12: 167–205.
- 347 9. Oxborough D, George K, Birch KM. Intraobserver reliability of two-dimensional
348 ultrasound derived strain imaging in the assessment of the left ventricle, right ventricle,
349 and left atrium of healthy human hearts. *Echocardiogr Mt Kisco N* 2012; 29: 793–802.
- 350 10. Binnetoğlu FK, Babaoğlu K, Altun G, et al. Effects that different types of sports have on
351 the hearts of children and adolescents and the value of two-dimensional strain-strain-
352 rate echocardiography. *Pediatr Cardiol* 2014; 35: 126–139.
- 353 11. Bjerring AW, Landgraff HE, Leirstein S, et al. Morphological changes and myocardial
354 function assessed by traditional and novel echocardiographic methods in preadolescent
355 athlete’s heart. *Eur J Prev Cardiol* 2018; 25: 1000–1007.
- 356 12. Charfeddine S, Mallek S, Triki F, et al. Echocardiographic analysis of the left
357 ventricular function in young athletes: a focus on speckle tracking imaging. *Pan Afr*
358 *Med J*; 25. Epub ahead of print 16 November 2016. DOI:
359 10.11604/pamj.2016.25.171.9095.
- 360 13. Małek ŁA, Barczuk-Falecka M, Brzewski M. Cardiac deformation parameters and
361 rotational mechanics by cardiac magnetic resonance feature tracking in pre-adolescent
362 male soccer players. *Cardiol Young* 2018; 1–3.
- 363 14. Rowland TW, Garrard M, Marwood S, et al. Myocardial performance during
364 progressive exercise in athletic adolescent males. *Med Sci Sports Exerc* 2009; 41: 1721–
365 1728.

- 366 15. Sherar LB, Mirwald RL, Baxter-Jones ADG, et al. Prediction of adult height using
367 maturity-based cumulative height velocity curves. *J Pediatr* 2005; 147: 508–514.
- 368 16. Mosteller RD. Simplified calculation of body-surface area. *N Engl J Med* 1987; 317:
369 1098.
- 370 17. Lang RM, Badano LP, Mor-Avi V, et al. Recommendations for Cardiac Chamber
371 Quantification by Echocardiography in Adults: An Update from the American Society
372 of Echocardiography and the European Association of Cardiovascular Imaging. *Eur*
373 *Heart J – Cardiovasc Imaging* 2015; 16: 233–271.
- 374 18. Oxborough D, Heemels A, Somauroo J, et al. Left and right ventricular longitudinal
375 strain-volume/area relationships in elite athletes. *Int J Cardiovasc Imaging* 2016; 32:
376 1199–1211.
- 377 19. Khouri MG, Peshock RM, Ayers CR, et al. A 4-tiered classification of left ventricular
378 hypertrophy based on left ventricular geometry: the Dallas heart study. *Circ Cardiovasc*
379 *Imaging* 2010; 3: 164–171.
- 380 20. van Dalen BM, Kauer F, Vletter WB, et al. Influence of cardiac shape on left ventricular
381 twist. *J Appl Physiol* 2009; 108: 146–151.
- 382 21. Unnithan VB, Rowland T, Lindley MR, et al. Cardiac strain during upright cycle
383 ergometry in adolescent males. *Echocardiogr Mt Kisco N* 2015; 32: 638–643.
- 384 22. The jamovi project. jamovi. (version 0.9) [computer software], <https://www.jamovi.org>
385 (2019).
- 386 23. Koch G, Röcker L. Plasma volume and intravascular protein masses in trained boys and
387 fit young men. *J Appl Physiol* 1977; 43: 1085–1088.
- 388 24. Zdravkovic M, Perunicic J, Krotin M, et al. Echocardiographic study of early left
389 ventricular remodeling in highly trained preadolescent footballers. *J Sci Med Sport*
390 2010; 13: 602–606.
- 391 25. Beaumont A, Grace F, Richards J, et al. Left Ventricular Speckle Tracking-Derived
392 Cardiac Strain and Cardiac Twist Mechanics in Athletes: A Systematic Review and
393 Meta-Analysis of Controlled Studies. *Sports Med*. Epub ahead of print 26 November
394 2016. DOI: 10.1007/s40279-016-0644-4.
- 395 26. DAscenzi F, Caselli S, Solari M, et al. Novel echocardiographic techniques for the
396 evaluation of athletes heart: A focus on speckle-tracking echocardiography. *Eur J Prev*
397 *Cardiol* 2016; 23: 437–446.
- 398 27. Forsythe L, MacIver DH, Johnson C, et al. The relationship between left ventricular
399 structure and function in the elite rugby football league athlete as determined by
400 conventional echocardiography and myocardial strain imaging. *Int J Cardiol* 2018; 261:
401 211–217.
- 402 28. Weiner RB, DeLuca JR, Wang F, et al. Exercise-Induced Left Ventricular Remodeling
403 Among Competitive Athletes A Phasic Phenomenon. *Circ Cardiovasc Imaging* 2015; 8:
404 e003651.

- 405 29. Weiner RB, Weyman AE, Khan AM, et al. Preload Dependency of Left Ventricular
406 Torsion: The Impact of Normal Saline Infusion. *Circ Cardiovasc Imaging* 2010; 3: 672–
407 678.
- 408 30. Blessberger H, Binder T. Two dimensional speckle tracking echocardiography: basic
409 principles. *Heart* 2010; 96: 716–722.
- 410 31. Malhotra A, Dhutia H, Finocchiaro G, et al. Outcomes of Cardiac Screening in
411 Adolescent Soccer Players. *N Engl J Med*. Epub ahead of print 8 August 2018. DOI:
412 10.1056/NEJMoa1714719.
- 413 32. Forsythe L, George K, Oxborough D. Speckle Tracking Echocardiography for the
414 Assessment of the Athlete’s Heart: Is It Ready for Daily Practice? *Curr Treat Options*
415 *Cardiovasc Med*; 20. Epub ahead of print October 2018. DOI: 10.1007/s11936-018-
416 0677-0.
- 417 33. Zhang Y, Zhou Q, Pu D, et al. Differences in Left Ventricular Twist Related to Age:
418 Speckle Tracking Echocardiographic Data for Healthy Volunteers from Neonate to Age
419 70 Years. *Echocardiography* 2010; 27: 1205–1210.
- 420 34. Notomi Y, Srinath G, Shiota T, et al. Maturational and adaptive modulation of left
421 ventricular torsional biomechanics: Doppler tissue imaging observation from infancy to
422 adulthood. *Circulation* 2006; 113: 2534–2541.

423

424

425

426 Figure legend:

427 **Fig. 1. Temporal analyses of left ventricle longitudinal strain (A) and strain rate (B) during the**
428 **cardiac cycle in soccer players (SP) and controls (CON). Data are means ± standard deviation.**
429 **AVC, aortic valve closure. Shaded areas indicate statistical significance at $p < 0.05$.**

430 **Tables**431 **Table 1** Left ventricular structure and volumes in soccer players (SP) and controls (CON).

	SP	CON	p-value
HR (beats/min)	65 ± 8	74 ± 10	0.005
LVEDd (mm)	42 ± 4	44 ± 4	0.142
LVEDd index (mm/(m ²) ^{0.5})	37 ± 3	38 ± 3	0.343
LVESd (mm)	28 ± 3	29 ± 3	0.403
LVESd index (mm/(m ²) ^{0.5})	25 ± 3	25 ± 2	0.725
MWT (mm)	6.0 ± 0.4	6.1 ± 0.5	0.754
MWT (mm/(m ²) ^{0.5})	5.3 ± 0.4	5.3 ± 0.5	0.769
RWT	0.29 ± 0.04	0.28 ± 0.04	0.387
LVM (g)	75 ± 14	82 ± 18	0.204
LVM index (g/m ²)	25 ± 5	28 ± 7	0.051
LV length (mm)	76 ± 6	74 ± 5	0.316
LV length index (mm/(m ²) ^{0.5})	67 ± 5	64 ± 5	0.140
LVEDV (mL)	75 ± 10	69 ± 15	0.106
LVEDV index (mm/(m ²) ^{1.5})	51 ± 8	45 ± 6	0.007
LVESV (mL)	26 ± 4	26 ± 8	0.696
LVESV index (mL/(m ²) ^{0.5})	18 ± 2	17 ± 3	0.625
Concentricity (g/mL) ^{0.667})	4.3 ± 0.7	4.9 ± 1.0	0.017
Sphericity index	1.8 ± 0.2	1.7 ± 0.1	0.034
SV (mL)	49 ± 8	43 ± 10	0.031
SV index (mL/(m ²) ^{1.0})	38 ± 6	32 ± 5	0.002
Q̇ (L/min)	3.19 ± 0.63	3.12 ± 0.67	0.741
Cardiac index (L/min/(m ²) ^{1.0})	2.48 ± 0.46	2.36 ± 0.42	0.391

432

433

434 Data are mean \pm standard deviation. HR, heart rate; LVEDd, left ventricular end-diastolic diameter;
435 LVESd, left ventricular end-systolic diameter MWT, mean wall thickness; RWT, relative wall
436 thickness; LVM, left ventricular mass; LVEDV, left ventricular end-diastolic volume; LVESV, left
437 ventricular end-systolic volume; SV, stroke volume; \dot{Q} , cardiac output; SP, soccer players; CON,
438 controls.

439

440

441

442

443

444

445

446

447

448

449

450

451

452

453

454

455

456

457

458

459

460

461

462 **Table 2.** Peak left ventricular mechanics in soccer players (SP) and controls (CON).

	SP	CON	p-value
<i>Longitudinal</i>			
Strain (%)	-20.3 ± 1.6	-19.6 ± 2.5	0.283
SRS (s ⁻¹)	-1.07 ± 0.11	-1.11 ± 0.18	0.427
SRE (s ⁻¹)	2.22 ± 0.40	2.02 ± 0.46	0.025
SRA (s ⁻¹)	0.57 ± 0.10	0.66 ± 0.15	0.105
<i>Mitral Valve (Base)</i>			
Circumferential strain (%)	-22.2 ± 2.5	-20.5 ± 2.5	0.029
Circumferential SRS (s ⁻¹)	-1.29 ± 0.15	-1.29 ± 0.17	0.925
Circumferential SRE (s ⁻¹)	2.16 ± 0.37	2.08 ± 0.34	0.457
Circumferential SRA (s ⁻¹)	0.36 ± 0.13	0.38 ± 0.09	0.587
Radial strain (%)	38.3 ± 13.7	33.7 ± 15.4	0.304
Radial SRS (s ⁻¹)	2.12 ± 0.50	2.22 ± 1.01	0.675
Radial SRE (s ⁻¹)	-2.54 ± 0.81	-2.46 ± 0.81	0.954
Radial SRA (s ⁻¹)	-0.74 ± 0.36	-1.08 ± 0.67	0.065
<i>Papillary Muscle (mid-ventricular)</i>			
Circumferential strain (%)	-20.1 ± 1.5	-18.3 ± 2.5	0.007
Circumferential SRS (s ⁻¹)	-1.17 ± 0.17	-1.19 ± 0.18	0.732
Circumferential SRE (s ⁻¹)	1.89 ± 0.33	1.57 ± 0.39	0.001
Circumferential SRA (s ⁻¹)	0.37 ± 0.14	0.42 ± 0.12	0.215
Radial strain (%)	61.6 ± 15.8	62.2 ± 20.9	0.918
Radial SRS (s ⁻¹)	2.38 ± 0.89	2.47 ± 1.28	0.944
Radial SRE (s ⁻¹)	-3.64 ± 1.54	-3.35 ± 1.47	0.569
Radial SRA (s ⁻¹)	-1.08 ± 0.54	-1.60 ± 1.54	0.463
<i>Twist Mechanics</i>			
Apical rotation (°)	11.95 ± 5.31	7.58 ± 3.55	0.005

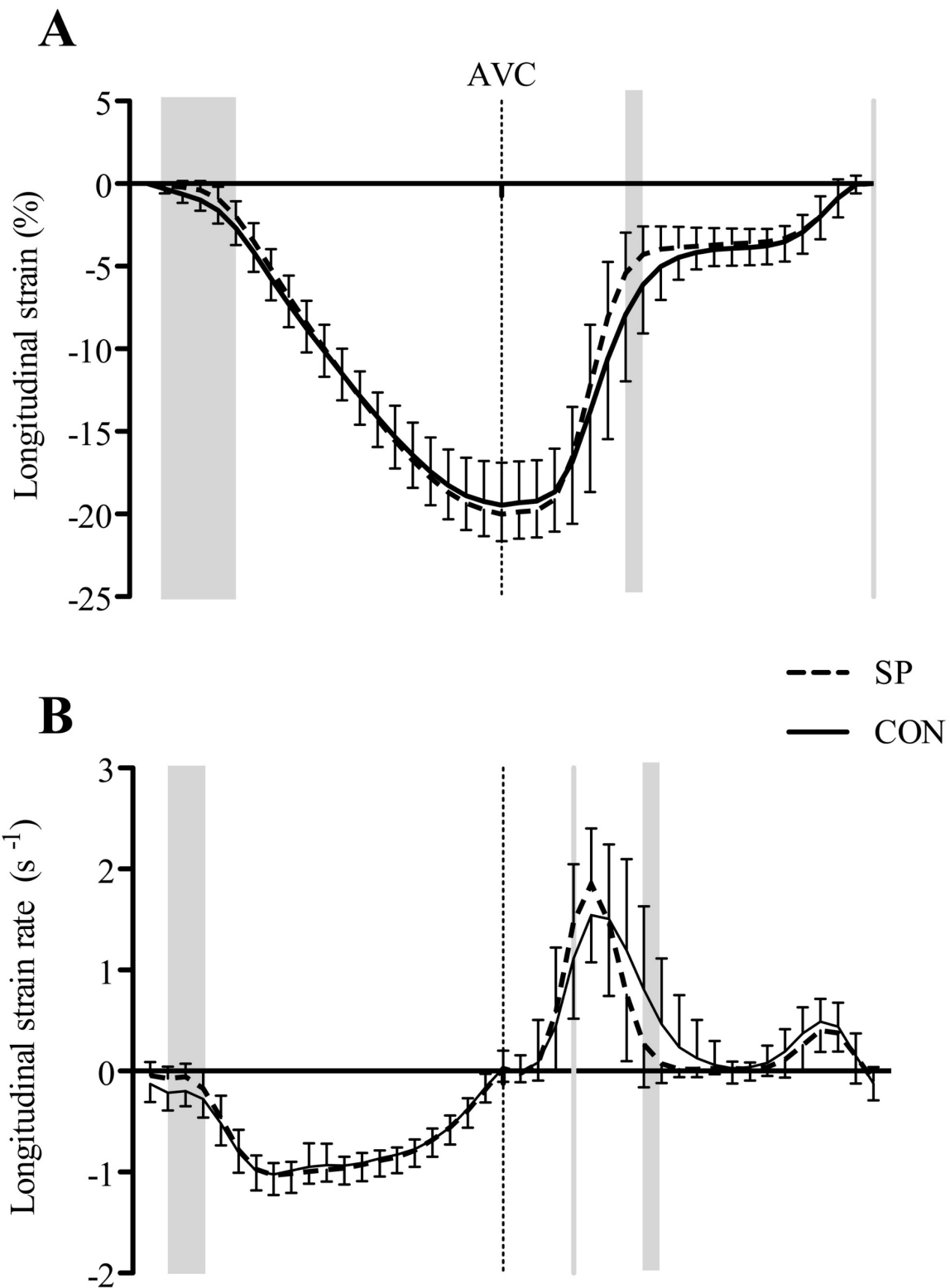
Basal rotation (°)	-5.69 ± 3.14	-5.64 ± 2.65	0.959
Twist (°)	16.92 ± 7.55	12.34 ± 4.99	0.035

463

464 Data are presented as means ± standard deviation. SRS, peak systolic strain rate; SRE, peak early
465 diastolic strain rate; SRA, peak late diastolic strain rate.

466

467



469

470

471