Differences in Left Ventricular Function at Rest and During Isometric Handgrip Exercise in Elite Swimmers, Water Polo Players, and Artistic Swimmers

Received: 18 June 2021
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Please cite as: Coates, A.M., Cheung, C.P., Currie, K.D., King, T.J., Mountjoy, M.L., & Burr, J.F. (2021). Cardiac remodeling in elite aquatic sport athletes. *SportRxiv*. DOI: [10.31236/osf.io/pyvts](https://doi.org/10.31236/osf.io/pyvts)

Conflicts of Interest and Source of Funding: Travel and accommodation for this project was supported by the Federation Internationale de Natation, with laboratory equipment and personnel supported by the Canadian Foundation for Innovation and Natural Science Engineering Research Council. The authors have no conflicts of interest to declare.

All authors have read and approved this version of the manuscript. This article was last modified on June 22, 2021. Authors A.M.C @superalex_c and J.F.B @Dr_Burr can be reached on Twitter.

ABSTRACT

Purpose: Elite swimmers (SW) have reduced diastolic function compared to elite runners, possibly as an adaptation to the aquatic training environment. Water polo players (WP) and artistic swimmers (AS) are exposed to the same hydrostatic pressures as SW, but are subject to different training intensities, postures, and hemodynamic stressors. Our purpose was to compare resting and exercising cardiac function in elite SW, WP, and AS, to characterize the influence of training for aquatic-sport on left ventricular (LV) adaptation.

Methods: Ninety athletes (SW:20M/17F; WP:21M/9F; AS:23F) at the 2019 FINA World Championships volunteered for resting and stress (3min 30% maximal isometric handgrip) echocardiographic assessment of LV global function and mechanics.

Results: Male SW displayed improved resting systolic and diastolic function compared to WP; however, both groups maintained stroke volume under high-pressure handgrip stress (SW: $\Delta-4\pm12\%$; WP: $\Delta-1\pm13\%$, $P=0.11$). There were no differences between female SW and WP resting LV function, but SW demonstrated improved function over AS. During isometric handgrip, all female sport athletes maintained stroke volume (SW: $\Delta3\pm16\%$; WP: $\Delta-10\pm11\%$; AS: $\Delta-2\pm14\%$, $P=0.46$), but WP had improved apical rotation ($\Delta1.7\pm4.5^\circ$), which was reduced in AS ($\Delta-3.1\pm4.5^\circ$) and maintained in SW ($\Delta-0.5\pm3.8^\circ$, $P=0.04$). Unlike SW and WP, AS displayed a unique maintenance of early filling velocity during handgrip exercise (SW: $\Delta-3.5\pm14.7\text{cm/s}$; WP: $\Delta-15.1\pm10.8\text{cm/s}$; AS: $\Delta1.5\pm15.3\text{cm/s}$, $P=0.02$).

Conclusion: Among male athletes, SW display primarily volume-based functional adaptations distinct from the mixed volume-pressure adaptations of WP; however, both groups can maintain stroke volume with increased afterload. Female SW and WP do not demonstrate sport-specific differences like males, perhaps owing to sex-differences in adaptation, but have greater volume-based adaptations than AS. Lastly, AS display unique functional adaptations, that may be driven by elevated pressures under low-volume conditions.

Keywords : swimming, water polo, synchronized swimming, artistic swimming, echocardiography, cardiac mechanics

INTRODUCTION

From an evolutionary perspective, the human heart is well suited for endurance-type physical activity (1), allowing for increased cardiac output to be sustained under dynamic volume-stress conditions (1). However, the heart also possesses phenotypic plasticity that allows for adaptation to pressure-stress conditions, such as those that occur during static, or resistance-type, exercise (1, 2). Endurance athletes consistently exposed to dynamic volume-stress develop ventricular dilation with minimal wall thickening, and have improved diastolic function compared to the general population (1, 3, 4). In the presence of experimentally elevated blood volume (rapid saline infusion), these athletes are able to augment their stroke volume (SV); however, under static exercise pressure challenges (isometric handgrip) the maintenance of SV becomes untenable (1). In contrast, resistance-trained athletes who are commonly subjected to high pressure-stress in training do not manifest these volume-related adaptations and may develop left ventricular (LV) wall-thickening with no increase in internal chamber size (1, 5). This pressure driven remodelling supports the maintenance of systolic function, and can be associated with reductions in diastolic function compared to general populations (1, 4). Resistance athletes have the opposite responses to volume and pressure challenges as endurance athletes, with an inability to increase SV with rapid saline infusion, but a preservation of SV during high-pressure isometric handgrip exercise (1). As such, the function of the 'athlete's heart' (6, 7) depends on the hemodynamic and loading conditions that the athlete is subject to (1, 2), with elite athletes manifesting greater adaptations than lesser trained athletes (8).

Swimming is primarily an endurance sport, with high-volume and moderate-pressure hemodynamic components (2), and should elicit improved systolic and diastolic function through primarily volume-based adaptations (9). Elite swimmers' hearts demonstrate distinct functional changes at rest compared to land-based endurance athletes, with decreased diastolic untwisting and reduced early filling compared to runners of equal caliber (10). These divergent phenotypes may relate to the hydrostatic pressures and prone postures inherent to swim training, which may reduce the stimulus for diastolic adaptations (10) via augmentation of passive venous return (9). Reduced diastolic function in swimmers relative to runners could also be due to swimmers performing more resistance training (11), particularly of the upper body, than runners (12, 13). Water polo, while similar to swimming with a substantial endurance component to game-play, involves greater high-pressure stimuli through repeated bouts of strength-dependent high-intensity sprinting and grappling (14, 15). The differences in cardiac function between elite-level swimmers and water polo players of equal caliber have not yet been assessed.

Artistic swimmers (previously termed synchronized swimmers) may provide an additional unique case of cardiac adaptation. Artistic swimming is classified as a moderate-volume, moderate-pressure load sport, with artistic swimmers spending less time in endurance-based training than swimmers and water polo players, but with comparable levels of resistance training (2). Artistic swimmers are subjected to similar hydrostatic pressures as other aquatic athletes and, like water polo players, artistic swimmers commonly use a vertical body posture with both sustained and explosive efforts to vertically propel their bodies up in the water. Conversely, artistic swimming is unique as a substantial proportion of training time (43% of an average routine) is spent inverted (16). While swimmers and water polo players often undergo short duration breath-holds in training and competition, artistic swimmers spend up to 50% of their routine time in apnea (17), and must be able to hold their breath during dynamic exercise for upwards of 30s (18, 19). Underwater breath-holds, through the diving reflex, elicit elevations in arterial blood pressure, bradycardia (16), and reduced diastolic filling and SV, possibly secondary to elevated intrathoracic pressure (20). It is plausible that this pressure-stress could cause differential remodelling and functional adaptation compared to other aquatic sport athletes, although this has not been explored to date.

The purpose of this investigation was to characterize differences in cardiac function in elite swimming, water polo, and artistic swimming athletes participating in the Fédération Internationale de Natation (FINA) World Championships to understand how training load and environment may affect physiologic adaptation. A secondary purpose was to assess cardiac responses to an acute pressure challenge using isometric handgrip exercise to better understand the functional implication of the adaptations. It was hypothesized that of the three sports, swimmers would have the greatest volume-based adaptations as indicated by improved resting diastolic function, followed by water polo players, and then artistic swimmers. It was further hypothesized that under the high-pressure challenge, artistic swimmers would display the greatest maintenance of SV due to augmented high-pressure adaptations, followed by water polo athletes, and finally swimmers.

METHODS

Participants

Elite male and female swimmers, water polo players, and artistic swimmers ≥ 18 yr of age were recruited at the athlete's village in Gwangju, South Korea, during the 2019 FINA World Championships. Athletes attended testing outside of competition days (on a rest or recovery day), or after completion of all their events. All athletes provided written consent prior to testing, and the protocol was approved by IRB with further approval from the FINA

DOI: [10.31236/osf.io/pyvts](https://doi.org/10.31236/osf.io/pyvts)

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medical committee. Exclusion criteria included a lack of English proficiency that limited an athlete's ability to provide informed consent, and reporting of a previously diagnosed cardiovascular condition.

Baseline Measures

Athletes completed a medical and training history questionnaire which included questions regarding years of competitive training in their sport, average weekly training volume, and history of personal or familial cardiovascular disease. Standing height was measured at end-inspiration with a free-standing stadiometer (SECA; Hanover, MD, United States) and weight was measured with a calibrated electronic scale (Tanita TBF-300 WA; Arlington Heights, IL, United States), wearing no shoes and minimal clothing. Body surface area (BSA) was calculated using the Du Bois and Du Bois formula (21). Following anthropometry, athletes sat quietly with feet uncrossed and flat on the floor while brachial blood pressure was taken in triplicate using an automated oscillometric device (BpTRU, Coquitlam, BC, Canada). In a private temperature and humidity controlled medical examination room, athletes rested supine for ≥ 5 min prior to vascular measurements, which are outlined elsewhere (22), and resting supine brachial blood pressure and heart rate (HR) were also recorded with the Sphygmocor Xcel system (Atcor Medical; Sydney, Australia). Finally, participants performed two maximal isometric handgrip contractions, and the best of the two trials was considered the participant's maximal handgrip strength.

Echocardiographic Assessment

Echocardiographic images were collected in the left lateral decubitus position with two-dimensional echocardiography and Doppler imaging using a Vivid IQ ultrasound (GE Healthcare, Horten, Norway) and GE M5Sc (1.5-4.6 MHz) probe. Images were analyzed offline using EchoPAC software (EchoPAC; GE Healthcare, Horten, Norway) according to task force recommendations (23–25). Average values of three cardiac cycles were determined from images taken in the parasternal long and short-axis, apical 4-chamber, and apical 5-chamber views. Volumes were scaled allometrically to $BSA^{1.5}$ (8, 26). Morphological cardiac adaptations are presented in a companion study (27).

LV end-diastolic (LV EDV) and end-systolic volumes (LV ESV) were calculated using the modified Simpson's biplane method (24), with values used to compute ejection fraction (EF). Stroke volume was calculated as the product of LV outflow tract diameter and velocity time integral obtained from the apical 5-chamber view, with HR collected simultaneously. Pulsed-wave tissue Doppler imaging (TDI) was performed at the septal mitral annulus to determine systolic (S') and peak early (E') mitral annular velocities. Early (E) and late (A)

transmitral filling velocities were assessed using pulsed-wave Doppler at the mitral-valve leaflets. We report an inter-rater ICC of 0.97 for LV EDV, and 0.93 for E/A ratio.

Images captured in the basal and apical parasternal short-axis views, and apical 4-chamber views, were analyzed using speckle tracking software (EchoPAC; GE Healthcare, Horten, Norway) in accordance with current guidelines (23) to assess rotation, twist and torsion. Circumferential and radial strain were assessed using parasternal short axis views at the mid-level papillary muscles, with longitudinal strain assessed using apical 4-chamber. Raw traces were imported into post-processing software (2D Strain Analysis Tool, Stuttgart, Germany) to perform cubic spline interpolation, allowing for a normalized temporal display. Torsion was calculated by dividing twist by LV length.

Isometric Handgrip Exercise

Following resting echocardiographic assessment, participants remained in the left lateral decubitus position and completed a sustained 3min isometric handgrip test at 30% of maximal handgrip strength, while automated oscillometric blood pressure was taken each minute (BpTRU, Coquitlam, BC, Canada). Apical 4-chamber view for septal TDI, mitral-valve pulsed-wave Doppler, and longitudinal strain using speckle tracking analysis, 5-chamber view for velocity time integrals of the LV outflow tract, and parasternal short-axis apical and basal views to assess rotation and twist using speckle tracking analysis, were collected during the final 2min of the 3min exercise.

Statistical Analysis

Statistical analysis was performed using SPSS software (Version 26, IBM Corporation, Armonk, NY) and GraphPad Prism (Version 8, GraphPad Software Inc., La Jolla, CA). Statistical analyses were performed primarily within the same sex, owing to well-accepted cardiac differences between sexes (28). Univariate ANOVA was performed to assess between-group (sport) differences at rest. To assess functional alterations between sports with the isometric handgrip stimulus, a 2 (condition) x 3 (sport, females), or 2 (condition) x 2 (sport, males) repeated measures ANOVA was performed, with “rest to handgrip” as the within-subject condition, and sport as the between-group variable. When differences were apparent, Tukey HSD *post-hoc* tests were used to correct for multiple comparisons. Pearson correlations were used to compare same-sex cardiac variables to self-reported training data including: total training time, length-swimming distance, resistance training time, and land-based aerobic training time, and also to examine associations with percent change in cardiac function (calculated as resting values subtracted from handgrip values, divided by resting values), and training and handgrip strength data. Only the systolic blood pressure response to the handgrip test was analyzed as a between-sex variable using Univariate

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ANOVA, to assess the effect of the handgrip stimulus in elevating afterload in males compared to females. Data is presented as mean $\pm$ standard deviation with significance set *a priori* at $P < 0.05$.

RESULTS

Participant Characteristics

Ninety athletes who met inclusion criteria volunteered and were included in the study. Across all sport groups, a majority of participants identified as being white (73% of males, 55% of females); however, there was a self-reported mix of races (see Table 1) and countries of origin. Given this imbalance, racial differences in cardiac function could not be assessed. As data was collected at the FINA World Championships (2019), athletes were considered the best available athletes from their respective countries. Thirteen of the 17 swimming females had FINA world rankings, with a range of 21-189 (86 ± 60) noting that a ranking of 1 indicates the fastest swimmer in the world for their given event. Nineteen of the 20 male swimmers had FINA world rankings, with a range of 41-159 (88 ± 31). The breakdown by race distance was: 50m: 9 males/4 females, 100m: 4males/5 females, 200m: 5males/8 females, 400m: 1 male/0 females, 800m: 1 male/0 females.

Female water polo players reported having trained in their sport for longer than female swimmers ($P = 0.01$), and also reported more land-based aerobic training per week than female swimmers ($P = 0.004$). Swimmers of both sexes reported greater length-swimming distances per week than other sports (all $P < 0.001$); however, all other training characteristics including total training volume, and resistance training hours, were similar between groups ($P > 0.05$, see Table 1).

Resting Cardiac Function

Males

Among male athletes, swimmers demonstrated elevated systolic function at rest compared to water polo athletes. Swimmers had a greater SV index than water polo athletes ($P = 0.001$), but not cardiac output index ($P = 0.07$), with similar resting HR ($P = 0.17$) (see Table 2). Male swimmers also had greater ejection fraction ($P = 0.04$), septal systolic tissue velocity S' ($P < 0.001$), mid circumferential strain ($P = 0.02$), peak twist ($P = 0.02$) and torsion ($P = 0.01$), and time to peak twist rate ($P = 0.03$), than water polo players. Diastolic function was greater in male swimmers than water polo players, with elevated E/A ratio ($P < 0.001$), E' ($P < 0.001$) and reduced estimated filling pressure (E/e' ratio, $P = 0.04$) (see Table 2). Swimming distance per week and total training hours per week were related to improved measures of systolic (S' , peak twist, time to peak twist) and diastolic (E/A ratio, E' , and E/e') function, while resistance training volume was related to increased filling pressure (see supplemental Table 1).

Table 1. Participant and training characteristics

	Males		Females		
	Swimming	Water Polo	Swimming	Water Polo	Artistic Swimming
Participant Characteristics					
Number (n)	20	21	17	9	23
Age (yr)	24±3	27±6	22±3	24±5	21±3
Height (cm)	184±7 ^w	190±6 ^s	174±8 ^a	173±4 ^a	165±5 ^{w,s}
Mass (kg)	81.3±8.6 ^w	94.9±8.0 ^s	68.4±8.5 ^a	67.2±4.3 ^a	59.0±6.9 ^{w,s}
Body mass index (kg/m ²)	24.1±1.6 ^w	26.3±2.3 ^s	22.6±1.8	22.4±1.3	21.7±2.1
Body surface area (m ²)	2.04±0.14 ^w	2.23±0.11 ^s	1.82±0.15 ^a	1.80±0.07 ^a	1.64±0.10 ^{w,s}
Seated systolic BP (mmHg)	118±10	121±9	110±8	110±9	111±10
Seated diastolic BP (mmHg)	78±8	75±10	72±6	70±12	72±8
Self-Reported Race ((n) %)					
White	(14) 70	(16) 76	(8) 47	(8) 89	(11) 48
Asian	(1) 5	(0) 0	(2) 12	(1) 11	(6) 26
Black	(1) 5	(2) 10	(1) 6	(0)	(0) 0
Other / mixed race	(4) 20	(3) 14	(6) 35	(0)	(6) 26
Training					
Years in sport (yr)	9±3	10±3	8±3 ^w	13±2 ^s	10±4
Training volume (h/wk)	23±5	19±9	19±9	16±6	24±12
Swimming distance (km/wk)	48±22 ^w	13±7 ^s	42±17 ^{w,a}	10±5 ^s	8±7 ^s
Resistance (h/wk)	5±6	4±2	3±2	2±3	2±2
Land-based aerobic (h/wk)	1±1	1±2	1±2 ^w	4±3 ^s	3±2

^aP<0.05 from artistic swimming. ^wP<0.05 from water polo of same sex. ^sP<0.05 from swimmers of same sex. BP, blood pressure. Data as Mean±SD.

Females

Female swimmers had a greater cardiac output index than artistic swimmers (P=0.005), but not water polo players (P=0.26). This effect that was driven by a greater SV index (P<0.001), as resting HRs were similar between groups (all P>0.05, see Table 2). Female swimmers had greater S' (P=0.008) than artistic swimmers but not water polo athletes (P=0.42). Finally, swimmers and water polo players displayed greater peak twist rate than artistic swimmers (P>0.05). Diastolic function was greater in female swimmers compared to artistic swimmers, with elevated E/A ratio (P=0.02) and early diastolic tissue velocity E' (P=0.008). Swimming distance per week was related to greater systolic (SV index, cardiac output index, S', time to peak twist rate) and diastolic (E/A ratio, E') function, while land-based aerobic training hours were related to reduced cardiac output index and E/A ratio (see supplemental Table 1).

Table 2. Resting left ventricular function in elite aquatic-sport athletes

	Males		Females		
	Swimming	Water Polo	Swimming	Water Polo	Artistic Swimming
Systolic Function					
<i>Minimal subjects (n)</i>	20	21	16	9	23
HR (bpm)	55±10	59±8	56±10	57±8	57±9
Supine SBP (mmHg)	105±15	103±10	99±12	96±14	96±8
SV (mL)	121±31	113±20	97±20 ^a	82±8	67±14 ^s
SV index (mL/(m ²) ^{1.5})	41±8 ^w	34±5 ^s	39±6 ^a	34±4	32±6 ^s
Q (L/min)	6.6±1.7	6.7±1.4	5.4±1.3 ^a	4.7±0.7	3.8±0.8 ^s
Q index (L/min/(m ²) ^{1.5})	2.2±0.5	2.0±0.4	2.2±0.4 ^a	1.9±0.3	1.8±0.3 ^s
Ejection fraction (%)	59±3 ^w	55±7 ^s	61±4	61±3	58±8
S' septal (cm/s)	14.7±2.3 ^w	11.4±1.8 ^s	14.8±2.0 ^a	14.0±1.2	13.3±1.1 ^s
Systolic Mechanics					
<i>Minimal subjects (n)</i>	17	17	14	8	21
Long peak strain (%)	-18.6±2.1	-17.9±2.1	-20.6±2.7	-20.4±2.4	-19.0±2.8
Mid circ strain (%)	-17.4±2.4 ^w	-15.1±3.4 ^s	-18.6±4.4	-20.5±2.3	-17.1±4.8
Mid radial strain (%)	42.5±11.2	44.5±15.6	34.3±9.6	50.2±19.8	45.8±17.5
Peak apical rotation (°)	8.8±2.8	7.0±3.9	7.3±3.7	4.8±2.1 ^a	8.5±3.27 ^w
Peak basal rotation (°)	-5.2±2.3	-4.1±3.1	-4.6±2.5	-5.1±3.1	-5.1±2.4
Peak twist (°)	13.5±4.1 ^w	10.0±4.1 ^s	10.8±2.6	9.7±4.5	13.0±4.0
TTP twist (% sys)	95±6	92±19	100±16	101±17	91±6
Peak twist rate (°/sec)	84.8±24.0	78.3±30.6	64.6±17.5 ^a	67.8±23.7 ^a	89.3±18.4 ^{w,s}
TTP twist rate (% sys)	58±12 ^w	49±13 ^s	60±14	62±12	50±10
Torsion (°/cm)	1.6±0.5 ^w	1.2±0.5 ^s	1.4±0.4	1.5±0.6	1.7±0.5
Diastolic Function					
<i>Minimal subjects (n)</i>	19	19	17	9	22
Supine DBP (mmHg)	61±14	55±8	57±11	55±15	55±8
E (cm/s)	85.3±15.3	77.5±14.1	93.1±15.2	94.1±12.0	93.9±8.1
E Deceleration time (ms)	250±91	207±44	232±70 ^a	192±51	179±43 ^s
E/A ratio	3.0±0.5 ^w	2.2±0.7 ^s	3.5±1.0 ^a	2.9±0.6	2.8±0.7 ^s
E' septal (cm/s)	14.7±2.3 ^w	11.4±1.8 ^s	14.8±2.0 ^a	14.0±1.2	13.3±1.1 ^s
E/e' ratio	6.0±1.5 ^w	7.0±1.4 ^s	6.4±1.3	6.8±1.0	7.1±0.8
Diastolic Mechanics					
<i>Minimal subjects (n)</i>	18	17	16	7	21
Peak untwist rate (°/s)	-85.2±21.7	-80.8±28.0	-79.7±20.0	-75.1±35.7	-88.0±30.0
TTP untwist rate (% dias)	10±4	21±28	14±15	6±2	9±8

Minimal subjects, smallest number of subjects used per category. HR, heart rate. SBP, systolic blood pressure. SV, stroke volume. Q, cardiac output. S', systolic mitral annular tissue velocity. Long, longitudinal. Mid, taken at papillary muscles of parasternal short axis. TTP, time to peak. % sys, percent of systole. DBP, diastolic blood pressure. E, peak early diastolic transmitral filling velocity. E/A ratio, early-to-late diastolic transmitral filling velocity ratio. E', early diastolic mitral annular tissue velocity. % dias, percent of diastole. ^aP<0.05 from artistic swimming. ^wP<0.05 from water polo of same sex. ^sP<0.05 from swimmers of same sex.

Cardiac Function in Response to Acute-Pressure Challenge

Males

During the isometric handgrip exercise, male athletes had similar alterations in cardiac function across sports, with maintenance of baseline group differences (see Figure 1, Table 3). SV, SV index, and SV augmentation (percent change) were not different between groups during handgrip (all $P > 0.05$). Handgrip strength throughout the test was related to reductions in basal rotation ($r = -0.57$, $P = 0.003$), but faster time to peak untwist rate ($r = -0.47$, $P = 0.02$), irrespective of sport.

Resistance training time per week was inversely related to percent change in E ($r = -0.40$, $P = 0.02$). Land-based aerobic training time was inversely related to percent change in E/A ratio ($r = -0.47$, $P = 0.008$) and positively associated with increased cardiac output ($r = 0.34$, $P = 0.04$).

Females

Systolic blood pressure was elevated to a greater degree in female water polo athletes than other sports during the isometric handgrip exercise (sport x condition interaction $P = 0.03$; Figure 1); however, the handgrip stimulus did not elicit the same elevation in systolic blood pressure in females as it did in males (females: $\Delta 11 \pm 13\%$ vs males: $\Delta 26 \pm 15\%$, $P < 0.001$). SV index was similar during isometric handgrip across sports, as was percent change in SV (all $P > 0.05$). Peak apical rotation was reduced in artistic swimmers, maintained in swimmers, and augmented in water polo players during handgrip (sport x condition $P = 0.04$, see Figure 1). When assessing changes in diastolic function during the acute pressure challenge, artistic swimmers displayed no change in early diastolic filling (E) ($P = 0.02$) compared to female water polo players who had reduced E (sport x condition, $P = 0.02$; see table 3). Similarly, artistic swimmers had no change to E/A ratio during isometric handgrip compared to reductions in water polo females ($P = 0.001$) and swimmers ($P = 0.02$) (sport x condition interaction, $P < 0.001$; see Figure 1). Lastly, time to peak untwist rate was greater in water polo athletes than the other two sports (sport x condition interaction, $P = 0.02$; swimmers, $P = 0.03$; artistic swimmers, $P = 0.03$). Handgrip strength throughout the test, resistance training volume, and systolic blood pressure during the handgrip test were not correlated with percent changes to cardiac function. Volume of land-based aerobic training was related to greater percent changes in basal rotation ($r = 0.36$, $P = 0.03$) and untwist rate ($r = 0.36$, $P = 0.03$) during handgrip exercise.

Figure 1. Alterations in left ventricular function during a 30%max isometric handgrip exercise across male and female elite aquatic sport athletes. ^a $P<0.05$ from artistic swimming. ^w $P<0.05$ from water polo of same sex. ^s $P<0.05$ from swimmers of same sex.

DOI: [10.31236/osf.io/pyvts](https://doi.org/10.31236/osf.io/pyvts)

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Table 3. Left ventricular function during a 30%max isometric handgrip exercise, and percent change from rest, in elite aquatic sport athletes

	Males				Females					
	Swimming		Water Polo		Swimming		Water Polo		Artistic Swimming	
	HG	Δ Rest (%)	HG	Δ Rest (%)	HG	Δ Rest (%)	HG	Δ Rest (%)	HG	Δ Rest (%)
Systolic Function										
<i>Minimal subjects (n)</i>	17		18		14		9		21	
HR (bpm)	74±16	34±23 ^w	73±12	22±11 ^s	65±12	17±15	71±11	25±14	65±14	13±13
SV (mL)	115±27	-4±12	111±24	-1±13	94±19 ^{a,w}	3±16	73±10 ^s	-10±11	66±17 ^s	-2±14
Q (L/min)	8.2±2.4	30±32	8.1±1	21±22	6.0±1.6 ^a	18±24	5.0±1.5	12±20	4.2±1.1 ^s	18±24
Q index (L/min/(m ²) ^{1.5})	2.9±0.8	30±32	2.4±0.6	21±22	2.5±0.6 ^a	18±24	2.2±0.5	12±20	2.0±0.4 ^s	18±24
Ejection fraction (%)	58±3 ^w	-1±7	55±6 ^s	0±13	62±4	0±7	55±8	-8±15	58±9	0±20
S' septal (cm/s)	10.0±4.1 ^w	-31±26	7.5±1.3 ^s	-32±14	9.3±3.0	-38±16	8.3±2.1	-40±5	8.4±1.6	-37±11
Systolic Mechanics										
<i>Minimal subjects (n)</i>	13		12		11		6		18	
Long peak strain (%)	-17.4±1.7	-5±14	-16.6±2.2	-8±8	-19.7±2.0	-2±9	-19.5±0.9	-4±10	-18.4±2.5	-3±16
Peak basal rotation (°)	-4.1±2.7	6±126	-4.9±3.5	65±187	-4.8±3.1	32±110	-4.0±2.9	15±104	-4.6±3.7	-7±87
Peak Twist (°)	12.0±4.4	-10±35	10.2±4.0	22±72	9.5±4.4	6±80	9.0±3.9	-3±30	9.2±4.6	-21±57
TTP twist (% sys)	87±12	-8±14 ^w	100±28	18±37 ^s	105±31	7±34	86±20	-14±22	91±11	0±13
Peak twist rate (°/sec)	93.4±41.4	14±54	77.6±25.9	11±57	62.1±18.7	7±50	80.9±34.3	24±49	67.1±23.4	-23±34
TTP twist rate (% sys)	43±15	-18±47	33±12	-28±29	57±17	-6±36	50±25	-17±40	50±17	7±50
Torsion (°/cm)	1.4±0.5	-10±35	1.2±0.5	22±72	1.3±0.6	11±85	1.5±0.4	5±30	1.2±0.6	-21±59
Diastolic Function										
<i>Minimal subjects (n)</i>	16		14		15		9		19	
DBP (mmHg)	82±16	37±24	80±15	44±29	64±10	15±21 ^w	73±9	42±32 ^{s,a}	65±9	19±20 ^w
E (cm/s)	82.6±18.6	-3±19	75.3±15.3	-3±13	90.8±13.2*	-3±14	79.0±14.1*	-16±11 ^a	95.7±13.8*	2±17 ^w
E Deceleration time (ms)	203±84	-16±28	184±36	-6±31	203±70	-11±22	196±38	11±43	166±40	-8±21
E'(cm/s)	13.2±2.8 ^w	-8±16	10.0±2.3 ^s	-10±22	14.3±2.2	-3±16	12.3±3.3	-13±23	12.7±2.3	-5±13
E/e' ratio	6.4±1.4 ^w	8±29	7.7±1.8 ^s	14±34	6.5±1.6	2±21	6.9±2.0	8±50	7.6±1.1	8±17
Diastolic Mechanics										
<i>Minimal subjects (n)</i>	13		12		13		7		19	
Peak untwist rate (°/s)	-97.7±30.3	17±51	-94.4±36.8	20±34	-78.9±18.2	7±35	-71.9±20.5	7±43	-72.4±24.7	-4±58
TTP untwist rate (% dias)	11±10	1±8	31±36	18±33	25±20*	11±24 ^w	55±38*	45±37 ^{s,a}	22±24*	12±24 ^w

Minimal subjects, smallest amount of subjects used per category. HG, handgrip exercise. HR, heart rate. SBP, systolic blood pressure. SV, stroke volume. Q, cardiac output. S', systolic mitral annular tissue velocity. Long, longitudinal. TTP, time to peak. % sys, percent of systole. DBP, diastolic blood pressure. E, peak early diastolic transmitral filling velocity. E/A ratio, early-to-late diastolic transmitral filling velocity ratio. E', early diastolic mitral annular tissue velocity. % dias, percent of diastole. * P<0.05, condition x sport interaction. ^aP<0.05 from artistic swimming. ^wP<0.05 from water polo of same sex.

^sP<0.05 from swimmers of same sex.

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DISCUSSION

The aim of this investigation was to assess differences in left ventricular function between elite aquatic sport athletes due to differing training exposures and hemodynamic stimuli, and whether an isometric handgrip exercise test acting as an acute pressure challenge would elicit different compensations in SV. It was determined that elite male swimmers displayed more volume-based functional remodelling than water polo players, with comparatively greater systolic and diastolic function at rest. Both male swimmers and water polo players had a similar response to isometric handgrip exercise, with unchanged SV. Conversely, female swimmers and water polo players had similar resting systolic function, and swimmers displayed greater resting systolic and diastolic function than artistic swimmers. In response to the pressure challenge, systolic alterations including SV compensation were similar across sports, but artistic swimmers demonstrated a unique maintenance of early diastolic filling.

LV function in male athletes

Swimming is primarily an endurance sport that should elicit volume-based eccentric remodelling, with LV dilation, proportional wall thickening, and improved resting diastolic function (1, 5, 11, 29). In the present investigation, more than half of the swimmers across both sexes could be classified as sprinters as they competed primarily in 50-100m race distances. Despite this, sprint-distance swimmers are known to undergo high volumes of endurance training (30), and the 50m-100m swimmers reported similar km/week compared to ≥ 200 m distance swimmers in this investigation. Elite swimmers competing in these same events have been shown to have similar cardiac structure and function to that of elite sprint and distance runners, but with reduced early diastolic function (10). Water polo players, by contrast, are exposed to a mixture of power, sprint, and endurance training, as well as high loads of resistance training (14, 15). They have been demonstrated to have lower aerobic fitness (VO_{2max}) than endurance athletes such as cyclists and triathletes, but have similar cardiac morphology to these athletes (14). The water polo players characterized here reported similar overall weekly training hours to swimmers, as well as similar resistance training hours, but much less weekly swimming distance. We demonstrated in a companion study that elite male water polo players had greater incidence of concentric geometry and elevated relative wall thickness than swimmers, indicative of augmented pressure-based remodelling (27). In accordance with our hypothesis and the sporting demands, it is clear that male swimmers have cardiac adaptations consistent with volume-based adaptations, while water polo males have a more mixed presentation. This is evidenced by greater SV index, torsion, diastolic E/A ratio, and reduced E/e' ratio in male swimmers compared to

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water polo players (31). Further, improved resting systolic and diastolic function was related to parameters of endurance training volume and aerobic fitness including weekly swimming distance and overall training volume.

Water polo players experience similar hydrostatic pressure as swimmers and, thus, the augmentation of venous return when in horizontal positions would be similar, which could alter diastolic adaptations compared to land-based athletes (10). However, water polo players spend less time training in horizontal postures with face-immersion compared to swimmers (15). Indeed, immersed subjects with their heads out of the water have an increase in cardiac output, while face-immersion causes reductions in cardiac output due to evocation of the dive-reflex (20). As water polo players perform more upright and face-out-of-water training, they could be expected to have improved diastolic function compared to swimmers from less passive venous-return, and less exposure to the dive-reflex. However, in this investigation, male swimmers had greater early diastolic filling, early diastolic tissue velocity, and reduced estimated filling-pressure compared to water polo players, indicative of improved ventricular compliance (32). High-level endurance training is thought to drive previously reported improvements in ventricular compliance and filling (1, 11, 31, 33), and compared to other aquatic sports, swimming training volume is a greater stimulus for diastolic adaptation than body posture in the water.

We expected that swimmers would have a reduction in SV during isometric handgrip compared to water polo players, as has been demonstrated when comparing American football linemen to runners (1), yet male athletes in both sports had maintenance of SV with no difference across sports. This suggests that male swimmers are better adapted to high-pressure stimuli than other endurance athletes (runners), which could be due to frequent exposure to upper-body resistance training and/or underwater breath-hold stimuli (20). It is notable that the hemodynamic environment from elite swim training may allow for ideal cardiac function under both volume and pressure exercise stress; although, the swimmer's heart under a specific volume challenge has not been investigated to date.

LV function in female athletes

Despite comparable reported training stimuli to the male athletes, female swimmers and water polo players had similar resting cardiac systolic and diastolic function to each other. This discrepancy in sport related differences across the sexes may relate to an overall predisposition of female athletes to volume-based adaptations (34), with less occurrence of resistance-based remodelling (35, 36). Accordingly, we did not see structural differences between female swimmers or water polo players in the companion study (27). With isometric handgrip exercise, water polo players generated greater elevations in systolic blood pressure than the other two sports, and water polo players demonstrated

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the largest percent reduction in SV, yet this difference was not significantly different from the other groups and there was no correlation between systolic blood pressure and change in SV. While it appears as though female aquatic athletes were generally able to maintain SV under high-pressure stimuli to a similar degree as male athletes, the handgrip stimulus did not elicit the same elevations in systolic blood pressure in female athletes, and a greater pressure stimulus might have resulted in a reduction in SV (37) as was noticed with the female water polo players.

Artistic swimming has received little attention to date in sports cardiology despite its severe physiological demands. While the aerobic fitness of artistic swimmers is typically less than that of swimmers (19), and may be similar to female water polo players (38), artistic swimmers are required to perform explosive lifts, aerobic skills, and head-down postures, often following extensive breath-holds which provide a repeated pressure stress (19). Artistic swimmers have a heightened dive reflex response, which reduces filling and cardiac output (reduced volume stress), while elevating arterial and intrathoracic pressure under water (16, 20). All of these heightened pressure-stressors should elicit LV alterations typically demonstrated with resistance training, including concentric LV remodelling; however, in our companion study we report AS to have presented with the most normal LV geometry compared to other aquatic sports, save isolated posterior-wall thickening (27). In this analysis artistic swimmers demonstrated reduced resting systolic and diastolic function compared to swimmers, with decreased SV index and Q index, S' , E/A ratio, and E' , representing an apparent reduction in volume-based adaptations. Artistic swimmers also had distinct cardiac mechanics from the other two sports, with elevated peak apical rotation compared to water polo, and peak twist rate at rest compared to both sports. This elevated resting apical rotation likely indicated less contractile reserve (31), and accordingly apical rotation was reduced during isometric handgrip exercise, compared to an elevation in rotation in water polo athletes. Despite this, there was evidence of improved diastolic performance during pressure-stress compared to the other two sports, as artistic swimmers maintained transmitral filling velocity ratio during isometric handgrip exercise, with similar blood pressure and HR responses to swimmers. This could represent an enhanced ability to maintain filling through elevated untwist rates, but could also be indicative of enhanced left atrial pressure generation occurring due to restrictive filling (39), which has been demonstrated to occur during diving (20). Artistic swimmers did demonstrate other characteristics of restrictive cardiomyopathies, including dilated left atria, shortened early diastolic deceleration times (27% of artistic swimmers displayed deceleration time <150 ms at rest), and increased filling pressures (E/e') (39). As resting echocardiographic parameters suggest the athletes were healthy, further clinical screening

is warranted to assess whether artistic swimmers develop a presentation of restrictive cardiomyopathy from their sporting demands.

Limitations

This study was performed in the athletes' village at the FINA World Championships (2019), therefore there were inevitable limitations with the design. A strength was the high caliber of athletes examined in this study, all of whom have trained at the highest level for many years and should have been at their peak fitness. However, we were unable to perform fitness testing other than evaluating maximal isometric handgrip strength. As such, any designation of an athlete being endurance or resistance trained was assumed based on their sport, previous research, and self-reported training data. Furthermore, due to the cross-sectional nature of this study, a cause-and-effect relationship between either training regimes or frequent exposure to sport-specific hemodynamic challenges and cardiac adaptations cannot be established. Finally, further work assessing aquatic athletes in response to different body postures, as well as volume stress, and during a more robust exercise challenge would be an important addition to this field.

Conclusions

Elite aquatic sport athletes demonstrate distinct cardiac function across sports. Amongst male athletes, there are clear volume-based adaptations in swimmers with improved systolic and diastolic function compared to water polo players; however, both sports had the same maintenance of function under pressure-challenge. This suggests the aquatic environment may drive pressure-based functional adaptations in swimmers, which is interesting considering morphology and resting function suggests swimmers undergo primarily endurance-based adaptations. In female athletes, there were no differences between water polo players and swimmers' hearts, which implies different training stresses or sex-differences in adaptation. Finally, artistic swimmers were demonstrated for the first time to have unique cardiac adaptations, with less volume-based adaptations compared to swimmers and water polo players, but with an ability to maintain early-diastolic filling velocity despite elevated pressure stress. Ultimately, these findings support the influence of both volume-and-pressure hemodynamic stimuli as for differential adaptation; however, the influence of the dive-reflex and underwater immersion may further influence functional adaptation. These findings are important for the characterization of sport-specific functional remodeling, which may help clinicians differentiate between physiological and pathological remodeling.

Acknowledgements

We would like to thank FINA and the FINA Sports Medicine Committee with special thanks to Dr. Jim Miller and the FINA cardiology sub-committee for supporting this research. We also would like to acknowledge GE Korea for providing us with ultrasound equipment and technical support at the World Championships, and Dr. Eric J. Stohr for providing the 2D Strain Analysis Tool software.

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DOI: [10.31236/osf.io/pyvts](https://doi.org/10.31236/osf.io/pyvts)

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