Unaltered left ventricular mechanics and remodelling after 12 weeks of resistance exercise training – A longitudinal study in men

Jason S. Au[1], Sara Y. Oikawa[1], Robert W. Morton[1], Stuart M. Phillips[1], Maureen J. MacDonald[1], Eric J. Stöhr[2,3]

[1]*Department of Kinesiology, McMaster University, Hamilton, Canada*

[2]*Discipline of Physiology & Health, Cardiff School of Sport, Cardiff Metropolitan University, Cardiff, Wales*

[3]*Department of Medicine, Columbia University Irving Medical Centre, New York, USA*

RUNNING HEAD: LV mechanics and resistance exercise training

Address for correspondence:
Maureen J. MacDonald, PhD
McMaster University
Department of Kinesiology
IWC E207, 1280 Main Street West
Hamilton, ON, Canada, L8S 4K1
Telephone: 905-525-9140 ext. 23580
Fax: 905-523-6011
Email: macdonmj@mcmaster.ca

Submitted to: *Applied Physiology, Nutrition and Metabolism*

Article Type: Article

Current author contact information: Jason S. Au (Schlegel-University of Waterloo Research Institute for Aging, University of Waterloo, Waterloo, Canada; jason.au@uwaterloo.ca)

ABSTRACT

Previous longitudinal studies suggest that left ventricular (LV) structure is unaltered with resistance exercise training (RT) in young men. However, evidence from aerobic exercise training suggests that early changes in functional LV wall mechanics may occur prior to and independently of changes in LV size, although short-term changes in LV mechanics and structural remodelling in response to RT protocols have not been reported. Therefore, the purpose of this study was to examine the effects of RT on LV mechanics in healthy men performing two different time-under-tension protocols. Forty recreationally-trained men (age: 23±3 years) were randomized into 12 weeks of whole-body higher-repetition RT (20-25 repetitions/set to failure at ~30-50% 1RM; n=13), lower-repetition RT (8-12 repetitions/set to failure at ~75-90% 1RM; n=13), or an active control period (n=14). Speckle tracking echocardiography was performed at baseline and following the intervention period. Neither RT program altered standard measures of LV volumes (end-diastolic volume, end-systolic volume, or ejection fraction; $P>0.05$) or indices of LV mechanics (total LV twist, untwisting rate, twist-to-shortening ratio, untwisting-to-twist ratio, or longitudinal strain; $P>0.05$). This is the first longitudinal study to assess both LV size and mechanics after RT in healthy men, suggesting a maintenance of LV size and twist mechanics despite peripheral muscle adaptations to the training programs. These results provide no evidence for adverse LV structural or functional remodelling in response to RT in young men and support the positive role of RT in the maintenance of optimal cardiovascular function, even with strenuous RT.

KEYWORDS: left ventricular twist; resistance training; high-repetition resistance training; echocardiography; speckle-tracking; longitudinal strain;

INTRODUCTION

Resistance exercise is characterized by brief periods of high blood pressure (MacDougall et al. 1985), the magnitude of which increases with increasing number of repetitions and heavier loads (MacDougall et al. 1992, Gjøvaag et al. 2016). Additionally, loading of the left ventricle (LV) and sympathetic activation will impact on the heart's stress exposure. While LV wall stress may be maintained during resistance efforts with concomitant Valsalva-mediated increases in intrathoracic pressure (Haykowsky et al. 2001), acute exposure to RT has been reported to impact LV mechanics during, and following, low- and moderate-intensity efforts (Stöhr et al. 2017). While exercise-induced cardiac remodelling is described in detail elsewhere (Baggish et al. 2008, Naylor et al. 2008), the few interventional studies examining the impact of RT on cardiac structure and function in non-athletes suggest unaltered LV chamber dimensions with long-term RT (>3 months) (Spence et al. 2011, Scharf et al. 2017). However, evidence from intense aerobic exercise training suggests that early changes in LV function may occur prior to changes in LV structure observed beyond three months of training (Weiner et al. 2010a, 2015); to date, simultaneous observations of LV structure and function in longitudinal studies investigating RT are lacking.

The study of LV strain and twist (termed "LV wall mechanics") has recently garnered attention for the capacity to provide information on myocardial tissue deformation beyond that of LV geometry (Notomi et al. 2006, Wang et al. 2008, Mor-Avi et al. 2011, Schuster et al. 2016). Given the robust ability of the LV to eject ~60% of its volumetric contents for relatively small cardiomyocyte shortening (Krueger and Pollack 1975, Beyar and Sideman 1984), the study of LV deformation mechanics is thought to be integral to the examination of changes in cardiac function across the continuum of chronic disease and performance (Aelen et al. 1997, Stöhr et al. 2016). Resting differences in LV twist have been observed among resistance-trained male athletes

(Beaumont et al. 2017), suggesting an effect of RT of unknown cause. Despite the acute regulation of LV mechanics in pressure loading conditions (Dong et al. 1999, Weiner et al. 2010b, Balmain et al. 2016), and evidence of self-preservation of LV mechanics during increased afterload (van Mil et al. 2016, Stöhr et al. 2017), LV twist has been observed to change with 90 days of intense aerobic training in collegiate rowers (Weiner et al. 2015), indicating a propensity for exercise-induced changes in LV mechanics prior to structural LV remodelling. Prior RT studies in non-athletes have indicated unaltered LV structure without measurement of functional LV mechanics, which may have masked underlying changes in LV function in the initial stages of training (Spence et al. 2011, Scharf et al. 2017). It remains unknown whether exposure to different RT programs, employing different time-under-tension protocols that may impact LV afterload conditions and sympathetic activation, would differentially impact LV size and mechanics, specifically twist, in the early period of a training program.

The purpose of this study was to examine the effects of two RT programs with varying time-under-tension protocols (higher-repetition, lighter-load (HiR) *vs*. lower-repetition, heavier-load (LoR)) on LV wall mechanics in healthy, recreationally-trained men. We hypothesized that 12 weeks of RT would significantly increase LV wall mechanics with larger increases in the HiR group.

METHODS

Participants

Forty-six men were recruited for this study, the general methods of which have been previously published (Morton et al. 2016, Au et al. 2017). All men had a history of recreational RT for greater than two years (average 4±2 yrs), including at least two sessions per week (average 3.1±0.6

sessions per week) with at least one lower body session, but were not currently engaged in athlete training programs. Participants were excluded if they were obese (BMI $\geq$ 30 kg/m^2), had a history of smoking, or were taking supplements other than protein before starting the exercise protocol. Six participants were subsequently excluded due to poor echocardiographic image quality, resulting in a final sample of 40 men. The study protocol was approved by the Hamilton Integrated Research Ethics Board (14-333) and conforms to the *Declaration of Helsinki*, except for registration in a database. All participants gave verbal and written consent prior to enrolment in the study.

Protocol Overview

The exercise training protocol consisted of three months of supervised RT, as previously described (Morton et al. 2016, Au et al. 2017). Briefly, participants were stratified by lean body mass via dual-energy X-ray absorptiometry and were subsequently randomized into one of three groups. Baseline cardiovascular characteristics were not controlled during stratification and were therefore tested for group differences in *post hoc* analyses. The three groups were: higher-repetition lower-load RT [HiR; three sets of 20-25 repetitions per set to volitional failure, ~30-50% of 1 Repetition Maximum (1RM); n=13]; lower-repetition, higher-load RT (LoR: three sets of 8-12 repetitions per set to volitional failure, ~75-90% of 1RM; n=13); and, an active control group who were asked to maintain their physical activity throughout the 12 week period (CON; n=14). These RT intensities were selected as they likely elicit different pressure-loading patterns during a bout of exercise (i.e., HiR is exposed to a higher pressure load for a longer duration than LoR), and offer an interesting secondary comparison of RT protocols. Speckle tracking echocardiography was performed one week before and one week after the intervention period (>72 hours after the last training session).

Resistance training protocol. All exercise training sessions were supervised by a research team member at McMaster University. Participants performed RT four times per week, separated into two whole-body workouts: 1) inclined leg press, seated row, bench press, cable hamstring curl, and front planks; 2) shoulder press, bicep curls, triceps extension, wide grip pull downs, and knee extension. 1RM was reassessed at weeks 4, 7, and 10 to adjust the load to ensure training progression. Participants were asked to refrain from any form of exercise outside of the study protocol. Participants consumed 30g of whey protein (BioPRO, Davisco Food International, Le Sueur, MN) twice per day: on workout days, once immediately after exercise and once pre-sleep, or on non-training days, once in the morning and once pre-sleep.

Echocardiography. Speckle-tracking echocardiography was performed according to the latest official guidelines and expert recommendations (Mor-Avi et al. 2011, Stöhr et al. 2016). A 1.5-3.6 MHz phased array probe connected to a commercially available ultrasound unit (Vivid q; GE Medical Systems, Horten, Norway) was used for all scans, with the participants laying in the left lateral decubitus position after 10 minutes of supine rest. Brachial blood pressure was measured in triplicate using an automated oscillometric device in the supine position (Dinamap Pro 100; Critikon LCC, Tampa, FL, USA). LV volumes (i.e., end-diastolic volume, end-systolic volume, ejection fraction, stroke volume, and cardiac output) and dimensions (average wall thickness, relative wall thickness, internal diameter, and LV mass) were estimated from M-Mode analysis of the parasternal long-axis. All speckle-tracking images were acquired at 60-80 fps, adjusting depth and sector width to centre the LV while maximizing its area in the image. The parasternal short-axis basal plane was defined as the level of the LV at the tips of the mitral valve leaflets, while the apical plane was defined as the lowest plane of the LV in which the papillary muscles were not visible, and acquired from an apical window (not basal), as previously described (Stöhr et al.

2011). The apical four-chamber view minimized the sector width and depth to isolate the LV to improve the frame rate. Speckle-tracking images were analysed using commercially available software (EchoPAC v110.0.2; GE Medical Systems, Horten, Norway), after which traces were exported to a personal laptop for the detection of maximal values within the cardiac cycle (i.e., peak twist, twist velocity, untwisting rate, circumferential strain and longitudinal strain) (2DStrainAnalysis Tool, Stuttgart, Germany). For reporting, positive values indicate counter-clockwise rotation whereas negative values indicate clockwise rotation and shortening of the LV length (longitudinal strain). In order to estimate the balance between subendocardial and subepicardial forces (Lumens et al. 2006), twist-to-shortening ratio was calculated as previously described (van Mil et al. 2016). To determine the independent contribution of diastolic LV mechanics, which has previously been suggested to play an important role during an acute episode of resistance exercise (Stöhr et al. 2017), LV untwisting rate was also adjusted for the preceding LV twist magnitude and reported as untwist-to-twist ratio (Stöhr et al. 2017). All cardiac data were averaged over at least three cardiac cycles. The sonographer was a member of the research team (J.A.) and was therefore not blinded to the group allocations. Intra-class correlation coefficients for sonographer repeatability and intra-rater reliability of LV volume analysis were >0.94 and >0.96, respectively.

Sample Size Justification: As no previous longitudinal studies have examined LV twist after RT, sample size was justified based on the anticipated effect size of short-term changes in apical rotation (in the absence of published combined LV twist data) in collegiate rowers, which combines aerobic- and resistance-type training (Weiner et al. 2015). Estimating an intervention effect size of d=1.2 with 80% power and a two-tailed alpha of 0.05, eight participants per group would be sufficient to detect changes with 12-weeks of training (Faul et al. 2009). Additional

participants were included to adjust for anticipated data dropout during follow-up as well as reduced power with multiple intervention conditions.

Statistical Analysis: Statistical analyses were performed using IBM SPSS Statistics for Macintosh (version 20.0.0; IBM Corp., Armonk, N.Y., USA). Data were assessed for normality using the Shapiro-Wilk test and were found to be normally distributed. 2 x 3 (time x group) mixed-model ANOVAs with Tukey's HSD post-hoc tests were used to assess changes in LV mechanics across the training period. To preclude underpowered analysis for the effect of exercise training (this study was powered on the effects of aerobic training), we also ran a secondary analysis by collapsing the HiR and LoR groups together to examine the global effect of RT. Secondary analyses were performed by a 2 x 2 (time x group) mixed-model ANOVA with Tukey's HSD post-hoc tests. Pearson's correlations were used to examine any relationships at the individual level between changes in LV twist and changes in LV size outcomes. For all analyses, the acceptable level of significance was set at $\alpha = 0.05$.

RESULTS

Participant characteristics are listed in Table 1. At baseline, the CON group had lower resting mean arterial pressure than the HiR group (P=0.04). Training adherence was similarly high for both groups (HR: 97±3% *vs*. LR: 97±4; P=0.23). Previous reports from our group on the same cohort have demonstrated significant training effects with RT, regardless of training conditions; these data are provided to aid interpretation but has previously been published (Morton et al. 2016, Au et al. 2017). Total fat- and bone-free mass increased (64.6±1.1 to 65.8±1.1 kg; P=0.01) with no significant differences between groups. There was a significant increase in strength for leg press (355±10 to 480±11 kg; P<0.01) and bench press (97±3 to 109±3 kg; P<0.01), with significantly

196 greater increases in bench press for the LR group compared to the HR group (14±1 *vs.* 9±1 kg;
197 P=0.01). Arterial stiffness was similarly reduced in both training groups (6.3±0.7 to 5.8±0.7 m/s;
198 P<0.01) without any changes in blood pressure.

199 There were no training-induced changes, in any group, in indices of resting LV size
200 including LV mass, LV diastolic internal diameter, LV wall thickness, relative wall thickness, or
201 LV hemodynamics (all P>0.05; Table 2). Similarly, there were no changes in LV wall mechanics
202 with either HiR or LoR (Figure 1 and Figure 2), including basal rotation, apical rotation, LV twist,
203 untwisting rate, twist-to-shortening ratio or untwisting-to-twist ratio and longitudinal strain (all
204 P>0.05). When secondary analyses were repeated by collapsing the HiR and LoR groups into a
205 single RT group, there were also no observed changes in LV volumes or mechanics across the
206 intervention period. Furthermore, there were no correlations between changes in LV twist and LV
207 structural outcomes (LV mass: r=0.04, P=0.81; EDV: r=0.01, P=0.97; relative wall thickness:
208 r=0.10, P=0.60) (Figure 3).

209

210 DISCUSSION

211 We observed no significant changes in indices of LV size or function, or systolic or diastolic LV
212 mechanics in response to three months of either higher-repetition or lower-repetition RT. Despite
213 the known acute effects of a strength effort on LV mechanics (Stöhr et al. 2017), it may be that the
214 long-term RT-induced LV remodelling observed in previous cross-sectional analyses only occurs
215 with lifelong exposure to high volumes of intense exercise (Pluim et al. 1999, Naylor et al. 2008).
216 Notwithstanding, these findings support the positive role of RT in maintaining optimal
217 cardiovascular health concurrent with large increases in muscle mass and strength, even with
218 strenuous training efforts.

There have been limited investigations examining longitudinal changes in LV morphology with RT training in non-athletes, with reports indicating both increases (Scharf et al. 2017) and no changes (Spence et al. 2011) in MRI-measured LV volumes and LV strain after >6 months RT in untrained men. Corroborating the latter, we observed neither RT-related changes in EDV, ESV, SV, LV mass, or relative wall thickness, nor relationships between indications of LV size and function over the 12-weeks of RT. Furthermore, our data indicate that the three-month time course known to cause early twist adaptations in the hearts of LV endurance athletes (Weiner et al. 2015) does not appear to be present as a consequence of the same duration of RT. Compared to LV volumes, LV strain and twist mechanics are markers of myocardial deformation, which have been theorized to play roles in LV diastolic function (Notomi et al. 2006) and may provide more detailed depictions of myocardial abnormalities in heart failure conditions (Wang et al. 2008). Endurance training has been suggested to prevent the age-related changes in resting LV twist-untwist mechanics, potentially allowing higher twist reserves during exercise (Maufrais et al. 2014). LV twist has also been recently reported to be high in resistance trained athletes (Beaumont et al. 2017), although our results indicate no change in either LV strain or twist-untwist mechanics with three months of RT, possibly indicative of duration- or population-dependent effects.

In the context of exercise-induced LV remodelling, the three-month RT protocol used in this study represents a relatively short-term examination of the impact of exercise training on LV wall mechanics (Weiner and Baggish 2014). Cross-sectional studies in athletes presumably describe the effect of years, and even decades, of exposure to large volumes of exercise training, which contribute to exercise-induced cardiac remodelling. Men recruited for this study had a history of recreational resistance training, which may be argued to contribute to a 'ceiling-effect' for subsequent short-duration training. However, regardless of loading protocol, participants in

both groups demonstrated gains in lean body mass, whole-body strength and, importantly, reduced arterial stiffness (Morton et al. 2016, Au et al. 2017), albeit at a lower magnitude than untrained men (Mitchell et al. 2012), suggesting residual trainability for further physiological remodelling. The musculoskeletal changes across the training period are consistent with an elevated training volume, which is considered higher-intensity (to fatigue) and longer-duration (4 times per week) compared to current exercise recommendations for Canadian adults (Tremblay et al. 2011). Furthermore, the variability in LV volumes across the training period reported in this study are similar to MRI-derived volumes reported by Spence *et al*. (2011) in an untrained population, indicating an absence of prior LV remodelling. It is unknown whether individuals naïve to resistance training would experience similar non-changes in LV wall mechanics, particularly if the untrained heart was rapidly exposed to chronic loading challenges.

We did not observe any divergent changes in LV volumes or LV mechanics in response to either HiR or LoR RT, similar to our previous findings in strength, body composition, and vascular health in the same cohort (Morton et al. 2016, Au et al. 2017). This is in agreement with the effects of acute resistive efforts, where low and high intensities did not have a significantly different effect on systemic vascular resistance (and therefore afterload), LV wall stress, or carotid artery strain; although, all are elevated after resistance exercise (Black et al. 2016, Stöhr et al. 2017).. In controlled experiments, acute increases in afterload are associated with decreased LV twist (Dong et al. 1999, Balmain et al. 2016, van Mil et al. 2016), which has been thought to act as a physiological stimulus for LV changes over time. In line with these findings, LV twist is acutely reduced during resistance exercise-related pressure-loading without Valsalva with concomitant increases in LV wall stress immediately post-exercise (Weiner et al. 2012, Stöhr et al. 2017) However, the full time course (during and after exercise) of LV exposure to increased afterload

and transmural wall stress in different lifting protocols has not been fully elucidated (Haykowsky et al. 2001, Stöhr et al. 2017). We were unable to assess the cardiovascular loading stimulus during our RT protocol, and therefore it is unknown whether participants in the HiR condition made consistent use of the Valsalva manoeuvre during early repetitions at lower loads. Regardless of condition, participants were instructed to lift until volitional failure in each set of the exercises, which may have negated the hypothesized differences in the exercise pressor response. It is unknown whether a cardiovascular response 'ceiling' exists for varying %1RMs when the exercise duration persists until volitional failure, though previous work in patients with coronary artery disease suggests an effect of bout duration on the pressor response to exercise (Gjøvaag et al. 2016). Finally, both conditions likely elicited systemic sympathetic activation, which has been postulated to increase LV contractility and provide additional physiological stress exposure due to an increasing β-adrenoreceptor density from the LV base to apex (Mori et al. 1993). However, given the lack of changes over the training period, neither afterload nor sympathetic factors likely played a large role in regulating LV mechanics with 12 weeks of RT.

Limitations: Estimations of LV volumes by M-Mode echocardiography are limited by symmetric assumptions of LV geometry. While it would be more desirable to report biplane or 3D measurements of LV volumes, our methods adhered to recent echocardiographic recommendations to reduce the measurement error as much as possible with the available scans (Lang et al. 2015). As the study methodology was designed according to primary outcomes of muscle volume (Morton et al. 2016), baseline differences in resting blood pressure were not controlled as part of the randomization process. Even so, statistical correction for blood pressure did not influence the results of the study. This study was powered based on large effect sizes from collegiate rowers,

which may not be related to the recreationally-active men recruited for this study, or the isolated RT program performed in the present study. As the assessment of LV mechanics was performed at rest, it is uncertain whether stress echocardiography would have revealed more sensitive indications of LV remodelling across a three-month RT period. Given that previous studies have observed changes in LV mechanics with acute resistance exercise (Stöhr et al. 2017), future studies may find it valuable to assess the acute LV mechanics response to increased myocardial work (i.e., stress speckle-tracking echocardiography) in response to an exercise intervention.

CONCLUSION

LV mechanics were unaltered following 12 weeks of RT in healthy men concomitant with unaltered LV structure despite being exposed to a high volume of resistance exercise to failure. These novel findings suggest that exposure to short-term RT does not necessarily result in structural or functional changes in the LV, although longer interventional studies are necessary to elucidate the effects of RT in non-athletes.

ACKNOWLEDGEMENTS

This study was supported by funding from the Natural Sciences and Engineering Research Council to M.J.M. (DG # 238819-13) and S.M.P. (RGPIN-2015-04613). S.M.P. thanks the Canada Research Chairs Program for their support.

308 REFERENCES

309 Aelen, F.W., Arts, T., Sanders, D.G., Thelissen, G.R., Muijtjens, a M., Prinzen, F.W., and
310 Reneman, R.S. 1997. Relation between torsion and cross-sectional area change in the
311 human left ventricle. J Biomech **30**(3): 207–212. doi:10.1016/S0021-9290(96)00147-9.

312 Au, J.S., Oikawa, S.Y., Morton, R.W., MacDonald, M.J., and Phillips, S.M. 2017. Arterial
313 stiffness is reduced regardless of resistance training load in young men. Med. Sci. Sport.
314 Exerc. **49**(2): 342–348. doi:10.1249/MSS.0000000000001106.

315 Baggish, A.L., Wang, F., Weiner, R.B., Elinoff, J.M., Tournoux, F., Boland, A., Picard, M.H.,
316 Hutter Jr., A.M., and Wood, M.J. 2008. Training-specific changes in cardiac structure and
317 function: a prospective and longitudinal assessment of competitive athletes. J Appl Physiol
318 **104**(4): 1121–1128. doi:10.1152/japplphysiol.01170.2007.

319 Balmain, B., Stewart, G.M., Yamada, A., Chan, J., Haseler, L.J., and Sabapathy, S. 2016. The
320 impact of an experimentally induced increase in arterial blood pressure on left ventricular
321 twist mechanics. Exp. Physiol. **101**(1): 124–134. doi:10.1113/EP085423.

322 Beaumont, A., Grace, F., Richards, J., Hough, J., Oxborough, D., and Sculthorpe, N. 2017. Left
323 ventricular speckle tracking-derived cardiac strain and cardiac twist mechanics in athletes:
324 A systematic review and meta-analysis of controlled studies. Sport. Med. **47**(6): 1145–1170.
325 Springer International Publishing. doi:10.1007/s40279-016-0644-4.

326 Beyar, R., and Sideman, S. 1984. A computer study of the left ventricular performance based on
327 fiber structure, sarcomere dynamics, and transmural electrical propagation velocity. Circ
328 Res **55**(3): 358–375. doi:10.1161/01.RES.55.3.358.

Black, J.M., Stöhr, E.J., Stone, K., Pugh, C.J.A., Stembridge, M., Shave, R., and Esformes, J.I. 2016. The effect of an acute bout of resistance exercise on carotid artery strain and strain rate. Physiol. Rep. **4**(17): e12959. doi:10.14814/phy2.12959.

Dong, S., Hees, P.S., Huang, W., Buffer Jr., S.A., Weiss, J.L., and Shapiro, E.P. 1999. Independent effects of preload, afterload, and contractility on left ventricular torsion. Am J Physiol Hear. Circ Physiol **277**(46): H1053–H1060.

Faul, F., Erdfelder, E., Buchner, A., and Lang, A.-G. 2009. Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. Behav. Res. Methods **41**(4): 1149–1160. doi:10.3758/BRM.41.4.1149.

Gjøvaag, T.F., Mirtaheri, P., Simon, K., Berdal, G., Tuchel, I., Westlie, T., Bruusgaard, K.A., Nilsson, B.B., and Hisdal, J. 2016. Hemodynamic responses to resistance exercise in patients with coronary artery disease. Med. Sci. Sports Exerc. **48**(4): 581–588. doi:10.1249/MSS.0000000000000811.

Haykowsky, M., Taylor, D., Teo, K., Quinney, A., and Humen, H. 2001. Left ventricular wall stress during leg-press exercise performed with a brief valsalva maneuver. Chest **119**(1): 150–154. The American College of Chest Physicians. doi:10.1378/chest.119.1.150.

Krueger, J.W., and Pollack, G.H. 1975. Myocardial sarcomere dynamics during isometric contraction. J. Physiol. **251**(3): 627–643. doi:10.1113/jphysiol.1975.sp011112.

Lang, R.M., Badano, L.P., Mor-Avi, V., Afilalo, J., Armstrong, A., Ernande, L., Flachskampf, F.A., Foster, E., Goldstein, S.A., Kuznetsova, T., Lancellotti, P., Muraru, D., Picard, M.H., Rietzschel, E.R., Rudski, L., Spencer, K.T., Tsang, W., and Voigt, J.U. 2015.

Recommendations for cardiac chamber quantification by echocardiography in adults: An update from the American society of echocardiography and the European association of cardiovascular imaging. Eur. Heart J. Cardiovasc. Imaging **16**(3): 233–271. doi:10.1093/ehjci/jev014.

Lumens, J., Delhaas, T., Arts, T., Cowan, B.R., and Young, A.A. 2006. Impaired subendocardial contractile myofiber function in asymptomatic aged humans, as detected using MRI. Am. J. Physiol. Heart Circ. Physiol. **291**(4): H1573-9. doi:10.1152/ajpheart.00074.2006.

MacDougall, J.D., McKelvie, R.S., Moroz, D.E., Sale, D.G., McCartney, N., and Buick, F. 1992. Factors affecting blood pressure during heavy weight lifting and static contractions. J. Appl. Physiol. **73**(4): 1590–7.

MacDougall, J.D., Tuxen, D., Sale, D.G., Moroz, J.R., and Sutton, J.R. 1985. Arterial blood pressure response to heavy resistance exercise. J. Appl. Physiol. **58**(3): 785–790. doi:10.1016/J.AMJCARD.2005.08.035.

Maufrais, C., Schuster, I., Doucende, G., Vitiello, D., Rupp, T., Dauzat, M., Obert, P., and Nottin, S. 2014. Endurance training minimizes age-related changes of left ventricular twist-untwist mechanics. J. Am. Soc. Echocardiogr. **27**(11): 1208–1215. doi:10.1016/j.echo.2014.07.007.

van Mil, A.C.C.M., Pearson, J., Drane, A.L., Cockcroft, J.R., McDonnell, B.J., and Stöhr, E.J. 2016. Interaction between left ventricular twist mechanics and arterial haemodynamics during localised, non-metabolic hyperaemia with and without blood flow restriction. Exp. Physiol. **101**(4): 509–520. doi:10.1113/EP085623.

371 Mitchell, C.J., Churchward-Venne, T.A., West, D.W.D., Burd, N.A., Breen, L., Baker, S.K., and
372 Phillips, S.M. 2012. Resistance exercise load does not determine training-mediated
373 hypertrophic gains in young men. J. Appl. Physiol. **113**(1): 71–77.
374 doi:10.1152/japplphysiol.00307.2012.

375 Mor-Avi, V., Lang, R.M., Badano, L.P., Belohlavek, M., Cardim, N.M., Derumeaux, G.,
376 Galderisi, M., Marwick, T., Nagueh, S.F., Sengupta, P.P., Sicari, R., Smiseth, O.A.,
377 Smulevitz, B., Takeuchi, M., Thomas, J.D., Vannan, M., Voigt, J.U., and Zamorano, J.L.
378 2011. Current and evolving echocardiographic techniques for the quantitative evaluation of
379 cardiac mechanics: ASE/EAE consensus statement on methodology and indications
380 endorsed by the Japanese society of echocardiography. Eur. J. Echocardiogr. **12**(3): 167–
381 205. doi:10.1093/ejechocard/jer021.

382 Mori, H., Ishikawa, S., Kojima, S., Hayashi, J., Watanabe, Y., Hoffman, J.I.E., and Okino, H.
383 1993. Increased responsiveness of left ventricular apical myocardium to adrenergic stimuli.
384 Cardiovasc. Res. **27**(2): 192–198. doi:10.1093/cvr/27.2.192.

385 Morton, R.W., Oikawa, S.Y., Wavell, C.G., Mazara, N., McGlory, C., Quadrilatero, J., Baechler,
386 B.L., Baker, S.K., and Phillips, S.M. 2016. Neither load nor systemic hormones determine
387 resistance training-mediated hypertrophy or strength gains in resistance-trained young men.
388 J. Appl. Physiol. **121**(1): 129–138. doi:10.1152/japplphysiol.00154.2016.

389 Naylor, L.H., George, K., O'Driscoll, G., and Green, D.J. 2008. The athlete's heart: a
390 contemporary appraisal of the "Morganroth hypothesis". Sport. Med. **38**(1): 69–90.
391 doi:3816 [pii].

Notomi, Y., Martin-Miklovic, M.G., Oryszak, S.J., Shiota, T., Deserranno, D., Popovic, Z.B., Garcia, M.J., Greenberg, N.L., and Thomas, J.D. 2006. Enhanced ventricular untwisting during exercise: A mechanistic manifestation of elastic recoil described by doppler tissue imaging. Circulation **113**(21): 2524–2533. doi:10.1161/CIRCULATIONAHA.105.596502.

Perry, B.G., Schlader, Z.J., Barnes, M.J., Cochrane, D.J., Lucas, S.J.E., and Mündel, T. 2014. Hemodynamic response to upright resistance exercise: Effect of load and repetition. Med. Sci. Sports Exerc. **46**(3): 479–487. doi:10.1249/MSS.0b013e3182a7980f.

Pluim, B.M., Zwinderman, A.H., van der Laarse, A., and van der Wall, E.E. 1999. The athlete's heart : A meta-analysis of cardiac structure and function. Circulation **100**(3): 336–344. doi:10.1161/01.CIR.101.3.336.

Scharf, M., Oezdemir, D., Schmid, A., Kemmler, W., Von, S., May, M.S., Uder, M., and Lell, M.M. 2017. Myocardial adaption to HI(R)T in previously untrained men with a randomized, longitudinal cardiac MR imaging study (Physical adaptions in Untrained on Strength and Heart trial, PUSH-trial). PLoS One **12**(12): e0189204. doi:10.1371/journal.pone.0189204.

Schuster, A., Hor, K.N., Kowallick, J.T., Beerbaum, P., and Kutty, S. 2016. Cardiovascular magnetic resonance myocardial feature tracking: Concepts and clinical applications. Circ. Cardiovasc. Imaging **9**(4): 1–10. doi:10.1161/CIRCIMAGING.115.004077.

Spence, A.L., Naylor, L.H., Carter, H.H., Buck, C.L., Dembo, L., Murray, C.P., Watson, P., Oxborough, D., George, K.P., and Green, D.J. 2011. A prospective randomised longitudinal MRI study of left ventricular adaptation to endurance and resistance exercise training in

humans. J. Physiol. **589**(22): 5443–5452. doi:10.1113/jphysiol.2011.217125.

Stöhr, E.J., González-Alonso, J., and Shave, R. 2011. Left ventricular mechanical limitations to stroke volume in healthy humans during incremental exercise. Am. J. Physiol. Heart Circ. Physiol. **301**(2): H478–H487. doi:10.1152/ajpheart.00997.2011.

Stöhr, E.J., Shave, R.E., Baggish, A.L., and Weiner, R.B. 2016. Left ventricular twist mechanics in the context of normal physiology and cardiovascular disease: a review of studies using speckle tracking echocardiography. Am. J. Physiol. - Hear. Circ. Physiol. **311**(3): H633–H644. doi:10.1152/ajpheart.00104.2016.

Stöhr, E.J., Stembridge, M., Shave, R., Samuel, T.J., Stone, K., and Esformes, J.I. 2017. Systolic and diastolic left ventricular mechanics during and after resistance exercise. Med. Sci. Sport. Exerc. **49**(10): 2025–2031. doi:10.1249/MSS.0000000000001326.

Tremblay, M.S., Warburton, D.E.R., Janssen, I., Paterson, D.H., Latimer, A.E., Rhodes, R.E., Kho, M.E., Hicks, A., LeBlanc, A.G., Zehr, L., Murumets, K., and Duggan, M. 2011. New Canadian Physical Activity Guidelines. Appl. Physiol. Nutr. Metab. **36**(1): 36–46. doi:10.1139/H11-009.

Wang, J., Khoury, D.S., Yue, Y., Torre-Amione, G., and Nagueh, S.F. 2008. Preserved left ventricular twist and circumferential deformation, but depressed longitudinal and radial deformation in patients with diastolic heart failure. Eur. Heart J. **29**(10): 1283–1289. doi:10.1093/eurheartj/ehn141.

Weiner, R.B., and Baggish, A.L. 2014. Acute versus chronic exercise-induced left-ventricular remodeling. Expert Rev. Cardiovasc. Ther. **12**(11): 1243–1246.

doi:10.1586/14779072.2014.970178.

Weiner, R.B., Deluca, J.R., Wang, F., Lin, J., Wasfy, M.M., Berkstresser, B., Stöhr, E., Shave, R., Lewis, G.D., Hutter, A.M., Picard, M.H., and Baggish, A.L. 2015. Exercise-induced left ventricular remodeling among competitive athletes: A phasic phenomenon. Circ. Cardiovasc. Imaging **8**(12): 1–10. doi:10.1161/CIRCIMAGING.115.003651.

Weiner, R.B., Hutter, A.M., Wang, F., Kim, J., Weyman, A.E., Wood, M.J., Picard, M.H., and Baggish, A.L. 2010a. The impact of endurance exercise training on left ventricular torsion. JACC. Cardiovasc. Imaging **3**(10): 1001–1009. Elsevier Inc. doi:10.1016/j.jcmg.2010.08.003.

Weiner, R.B., Weyman, A.E., Khan, A.M., Reingold, J.S., Chen-Tournoux, A.A., Scherrer-Crosbie, M., Picard, M.H., Wang, T.J., and Baggish, A.L. 2010b. Preload dependency of left ventricular torsion the impact of normal saline infusion. Circ. Cardiovasc. Imaging **3**(6): 672–678. doi:10.1161/CIRCIMAGING.109.932921.

Weiner, R.B., Weyman, A.E., Kim, J.H., Wang, T.J., Picard, M.H., and Baggish, A.L. 2012. The impact of isometric handgrip testing on left ventricular twist mechanics. J. Physiol. **590**(20): 5141–5150. doi:10.1113/jphysiol.2012.236166.

FIGURE LEGENDS

FIGURE 1. LV apical (black) and basal (grey) rotation before (solid) and after (dashed) the 12-week intervention. Curves are expressed relatively to end-systolic time (100%). HiR = higher-repetition group; LoR = lower-repetition group; CON = control group.

FIGURE 2. LV mechanics before (white) and after (grey) the 12-week intervention. The boxed lines represent the 25^{th}, 50^{th} (median), and 75^{th} percentiles. The cross indicates the mean, and the bars represent the 95% confidence interval.

FIGURE 3. Scatterplot of correlations between the individual changes in left ventricular twist and left ventricular structure pooled between all groups (higher-repetition group (HiR), lower-repetition group (LoR), control group (CON)): left ventricular mass, left ventricular end diastolic volume, and relative wall thickness.