European Journal of Radiology 204 (2026) 113091

Contents lists available at ScienceDirect

European Journal of Radiology

journal homepage: www.elsevier.com/locate/ejrad

Long-term exposure of physical inactivity and MRI-derived left ventricular myocardial Function: Results from a population-based cohort

Philipp Franke [a], Thomas Geyer [a], Sophia Stöcklein [a], Olaf Dietrich [a], Bernd J. Wintersperger [a,b], Susanne Rospleszcz [c,d], Christopher L. Schlett [c], Fabian Bamberg [c], Annette Peters [d,e,f,g], Wolfgang Lieb [h], Roberto Lorbeer [a,g,*]

[a] Department of Radiology, LMU University Hospital, LMU Medizin, Ludwig-Maximilians-Universität München, Germany
[b] University Medical Imaging Toronto, University of Toronto, Toronto, ON, Canada
[c] Department of Diagnostic and Interventional Radiology, Medical Center-University of Freiburg, Faculty of Medicine, University of Freiburg, Freiburg im Breisgau, Germany
[d] Institute of Epidemiology, Helmholtz Zentrum München, Neuherberg, Germany
[e] Chair of Epidemiology, IBE, LMU Medizin, Ludwig-Maximilians-Universität München, Germany
[f] German Center for Diabetes Research (DZD e.V.), Neuherberg, Germany
[g] DZHK (German Centre for Cardiovascular Research), Partner site Munich Heart Alliance, Munich, Germany
[h] Institute of Epidemiology, Kiel University, Kiel, Germany

ARTICLE INFO

Keywords:
Physical activity
Left-ventricular function
Myocardial strain
Population cohort

ABSTRACT

Objective: The association of physical inactivity with subclinical alteration of cardiac structure and function is not well established. In the present study, we investigated this association with left-ventricular (LV) function assessed by advanced MRI strain analysis in a population-based cohort free of known cardiovascular disease (CVD).
Materials and Methods: We used data of an MRI sub-study of the community-based KORA (Cooperative Health Research in the Region of Augsburg) cohort with 360 participants (156 women; aged 39 to 73 years). Physical activity was assessed at three examination cycles (Exam 1 [baseline], at Exam 2 [7-years follow-up] and at Exam 3 [14-years follow-up]) of the KORA S4 cohort. The MRI-derived myocardial 2D feature-tracking strain examination was conducted at Exam 3 and included longitudinal, radial and circumferential global strain parameters. Associations between physical inactivity and strain values were investigated in cross-sectional and longitudinal analyses.
Results: Current physical inactivity (Exam 3) was associated with reduced longitudinal (β = -1.09%; 95%CI −2.02; −0.15. p = 0.023), radial (β = -2.64%; 95%CI −4.79; −0.49. p = 0.016), and circumferential strain (β = -0.90%; 95%CI −1.60; −0.20. p = 0.012). Similarly, past physical inactivity reported at baseline (Exam 1) was associated with reduced strain parameters. The more often physical inactivity was reported across the three examinations (two or three times) the more reduced were radial (β = -2.09%; 95%CI −3.71; −0.47. p = 0.012) and circumferential strain (β = -0.69%; 95%CI −1.22; −0.16. p = 0.011). These associations were stronger in men than in women.
Conclusion: In a population-based cohort without overt CVD, repeated self-reported leisure-time physical inactivity was consistently associated with lower MRI-derived LV strain parameters at Exam 3. These results indicate that sustained inactivity may be linked to subtle impairments in myocardial deformation detectable before clinical disease onset.

Introduction

Cardiovascular diseases (CVD) are a leading cause of morbidity and mortality worldwide. Although global CVD mortality has decreased in recent decades, ischemic heart disease remains the single leading cause of death globally [1].

Low physical activity is among the most important behavioral risk factors for CVD, alongside poor diet, smoking −including secondhand

* Corresponding author.
E-mail address: roberto.lorbeer@med.uni-muenchen.de (R. Lorbeer).

https://doi.org/10.1016/j.ejrad.2026.113091
Received 22 April 2026; Received in revised form 18 June 2026; Accepted 15 July 2026
Available online 16 July 2026

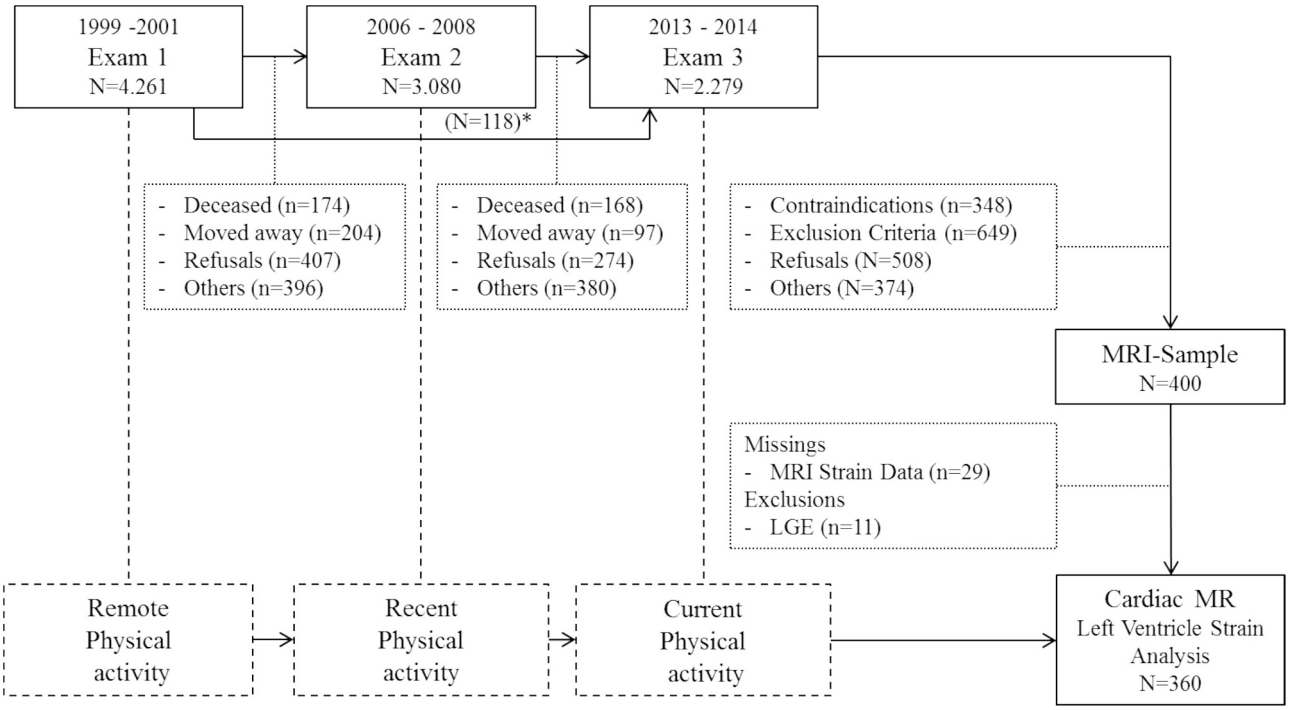

Fig. 1. Flow chart of the KORA MRI study sample and the cohort study design with repeated measurements of physical activity. (*N = 118 participants refused Exam 2, but attended Exam 3).

smoke-, and high alcohol use [2]. Physical inactivity is highly prevalent and is associated with reduced cardiovascular health, conferring an elevated risk for cardiovascular events such as myocardial infarction and stroke [3,4]. Therefore, increasing physical activity is critical in CVD prevention and treatment efforts [5,6].

Left ventricular (LV) function is pivotal in the cardiovascular system, sustaining life and maintaining optimal health. Subclinical alterations in LV structure and function often precede and predict clinical CVD events and CVD mortality [7,8], even after accounting for traditional risk factors.

In general population studies, echocardiographic measures of LV end-diastolic volume, end-systolic volume, ejection fraction, and LV mass have demonstrated associations between physical inactivity and subclinical impairments of LV structure and function [9,10]. Studies using cardiac magnetic resonance imaging (MRI) to investigate physical activity in relation to subclinical changes in LV function are less common, particularly in relatively healthy, population-based samples [11,12]. Notably, one MRI study reported that individuals with almost no physical activity had lower LV stroke volume and reduced LV ejection and filling rates [11], while another found that participants with higher exercise intensity had increased LV mass and end-diastolic volume [12].

MRI-derived strain parameters provide new insights into cardiac physiology and represent an emerging imaging biomarker of myocardial function. Previous investigations have shown that established cardiovascular risk factors, including diabetes mellitus, waist-to-hip ratio, and blood pressure, are associated with reduced global longitudinal, radial, and circumferential strain [13]. However, the association of physical inactivity on LV strain parameters in a population-based setting has not yet been studied, particularly from a longitudinal perspective. Therefore, we aimed to investigate the association between physical inactivity and LV myocardial function, as measured by MRI-based strain analysis, in a community cohort free of clinical CVD.

Methods

Study sample

The KORA S4 study ("Cooperative Health Research in the Region of Augsburg") is a population-based cohort conducted in the city of Augsburg (Bavaria) and two adjacent counties. The baseline examination (Exam 1) took place between 1999 and 2001 with 4,261 participants. Of these, 3,080 individuals also participated in the 7-year follow-up (2006–2008; Exam 2) and 2,279 participated in the 14-year follow-up (2013–2014; Exam 3). In the MRI sub-study, we included participants who attended Exam 3 and were eligible for MRI and who were free of overt CVD at the time of the examination since the primary aim of this analysis was to investigate subclinical alterations in LV function, defined as early myocardial changes in individuals without known clinical CVD. Restricting the sample to participants without clinically overt CVD was chosen to minimize confounding by indication and treatment related to established disease and to focus on the relation of physical activity with ventricular remodeling in a preclinical context. At Exam 3, a total of 400 participants without a history of stroke, myocardial infarction, or arterial vessel occlusion underwent a cardiac MRI at 3 Tesla [14]. Participants with missing strain data (n = 29) or evidence of late gadolinium enhancement (LGE, n = 11) on MRI were excluded, yielding a final sample of 360 participants (156 women; age 39–73 years) for the current analysis (Fig. 1).

Cardiac MRI

Cardiac MRI was performed on a clinical 3 T scanner (Magnetom Skyra, Siemens Healthineers, Erlangen, Germany). Cine images were obtained using a breath-hold balanced steady-state free precession (bSSFP) sequence with retrospective ECG gating, acquiring a 4-chamber view and contiguous short-axis slices covering the whole left ventricle (25 phases per cardiac cycle). Sequence parameters were: repetition time/echo time (TR/TE) 3.3/1.46 ms, temporal resolution 29.97 ms, slice thickness 8 mm (2 mm gap), field of view 360 × 297 mm^2, matrix

Table 1
Cardiovascular risk factors at Exam 3.

	Exam 3 (2013–2014) All (n = 360)	Women (n = 156)	Men (n = 204)	p
Age (years)	56.2 (±9.2)	56.4 (±9.2)	56.1 (±9.2)	0.706
Systolic BP (mmHg)	120.3 (±16.8)	113.2 (±14.5)	125.8 (±16.4)	<0.001
Diastolic BP (mmHg)	75.3 (±10.1)	71.9 (±8.6)	77.8 (±10.4)	<0.001
Hypertension	117 (32.5%)	44 (28.2%)	73 (35.8%)	0.128
Weight (kg)	82.2 (±16)	73.4 (±14.8)	88.9 (±13.5)	<0.001
Height (cm)	171.5 (±9.8)	163.4 (±6.6)	177.7 (±6.8)	<0.001
Body mass index (kg/m^2)	27.9 (±4.7)	27.5 (±5.4)	28.1 (±4)	0.210
Waist circumference (cm)	97.8 (±13.7)	91.6 (±13.8)	102.5 (±11.6)	<0.001
Hip circumference (cm)	106.5 (±8.6)	106.7 (±10.5)	106.3 (±6.9)	0.721
Waist-hip-ratio	0.92 (±0.09)	0.86 (±0.08)	0.96 (±0.07)	<0.001
Smoking status				0.126
Never-smoker	129 (35.8%)	64 (41%)	65 (31.9%)	
Ex-smoker	159 (44.2%)	60 (38.5%)	99 (48.5%)	
Current smoker	72 (20%)	32 (20.5%)	40 (19.6%)	
Pack-years	12.9 (±19)	8.3 (±12.2)	16.4 (±22.3)	<0.001
Alcohol consumption (g/day)	18.3 (±23.7)	8.8 (±14.2)	25.6 (±26.8)	<0.001
Diabetes mellitus	45 (12.5%)	12 (7.7%)	33 (16.2%)	0.016
HbA1c (%)	5.55 (±0.72)	5.55 (±0.56)	5.56 (±0.83)	0.943
Total cholesterol (mg/dl)	218.2 (±36.7)	219.8 (±35.4)	217 (±37.8)	0.474
HDL-C (mg/dl)	62.3 (±17.2)	70.3 (±17)	56.3 (±14.7)	<0.001
LDL-C (mg/dl)	139.6 (±33.3)	137.4 (±32.5)	141.3 (±33.9)	0.260
Antihypertensive medication	87 (24.2%)	42 (26.9%)	45 (22.1%)	0.285
Lipid-lowering medication	36 (10%)	17 (10.9%)	19 (9.3%)	0.620
Glucose-lowering medication	26 (7.2%)	10 (6.4%)	16 (7.8%)	0.603
Statin medication	36 (10%)	17 (10.9%)	19 (9.3%)	0.620

Data are given as number (percentage) or mean (± standard deviation). P-values are from two-sided *t*-test or chi-square test.
HbA1c, hemoglobin A1c; HDL-C, high-density-lipoprotein cholesterol; LDL-C, low-density-lipoprotein cholesterol.

240 × 198, flip angle 62°, in-plane voxel size 1.5 × 1.5 mm^2. LGE images were acquired ~ 10 min after intravenous gadobutrol (0.2 mmol/kg, Gadovist, Bayer Healthcare, Berlin, Germany).

Image data analysis

All image analyses were performed using a commercial post-processing software package (cvi42, version 4.1.5(190); Circle Cardiovascular Imaging Inc., Calgary, Canada). LV functional analysis was conducted by semiautomatic contouring of endocardial and epicardial borders on the short-axis cine bSSFP images, with manual adjustments as needed. Papillary muscles were considered part of the ventricular blood pool for volume analysis. After the LV contours were finalized for volumetric analysis, feature-tracking strain analysis was applied. The anterior and posterior right ventricular insertion points were identified, and the software then automatically tracked myocardial deformation throughout the cardiac cycle. The following global LV strain parameters were derived: (1) global radial strain (GRS), (2) global longitudinal strain (GLS), and (3) global circumferential strain (GCS). GLS was measured from the 4-chamber long-axis view, while GRS and GCS were derived from the short-axis image stack. Long-axis datasets were excluded if the LV outflow tract was partially included in the image. To assess reproducibility, strain analyses were repeated by the same observer after an interval of at least one week and by a second independent observer in a random subset of 30 subjects. All strain values were converted to absolute values (so that more positive values indicate better deformation) for statistical analysis and reporting.

Table 2
Left ventricular cardiac function and structure, obtained at Exam 3.

Left ventricular cardiac function and structure	Exam 3 (2013–2014) All (n = 360)	Women (n = 156)	Men (n = 204)	p
End-diastolic volume (ml)	129.2 (±33.19)	116.5 (±27)	138.8 (±34.2)	<0.001
End-systolic volume (ml)	40.6 (±18.2)	34.2 (±14.9)	45.4 (±19)	<0.001
Stroke volume (ml)	88.7 (±20.4)	82.3 (±17.4)	93.5 (±21.2)	<0.001
Ejection Fraction (%)	69.5 (±7.7)	71.3 (±6.9)	68.1 (±8)	<0.001
Myocardial mass, diastolic (g)	140.4 (±35.2)	114.9 (±25.9)	159.8 (±28.3)	<0.001
Myocardial mass, systolic (g)	142.9 (±39.1)	113.9 (±27.2)	164.9 (±31.6)	<0.001
Early diastolic filling rate (ml/s)	228.2 (±115.5)	226.5 (±106)	229.4 (±122.4)	0.817
Peak ejection rate (ml/s)	356.1 (±132.8)	330.3 (±108.8)	375.8 (±145.7)	0.001
Longitudinal Strain (%)	19.8 (±3.2)	21.0 (±2.9)	18.9 (±3.1)	<0.001
Radial Strain (%)	40.1 (±8.2)	43.5 (±7.5)	37.5 (±7.8)	<0.001
Circumferential Strain (%)	19.9 (±2.69)	21.1 (±2.3)	19 (±2.6)	<0.001

Data are given as mean (± standard deviation). P-values are from two-sided *t*-test.

Physical activity measurements

Standardized interviews were used to assess physical activity at Exam 1, Exam 2, and Exam 3 [15]. The primary domain of interest was leisure-time sporting activity; at Exam 3, additional domains (occupational, walking, and cycling activity) were also evaluated.

According to the study protocol, participants were classified as physically active if they reported regular exercise during both summer and winter months (year-round regular activity). Based on self-reported exercise frequency and regularity, four categories of leisure activity were defined: (a) no physical activity, (b) irregular physical activity (approximately 1 h per week), (c) regular physical activity (1 h per week), and (d) regular physical activity (≥2 h per week). For analysis, we additionally collapsed these into a binary classification of physical inactivity vs. activity: participants falling into categories (a) and (b) (no or ≤ 1 h per week of irregular activity) were considered physically inactive, whereas those in categories (c) or (d) (≥1 h per week of regular activity) were considered physically active.

Using the longitudinal data from the three examinations, we developed an index of long-term exposure to reported regular physical activity (≥1 h/week): (a) active at all three exams (regularly active over ~ 14 years), (b) active at two of the three exams, (c) active at only one exam, or (d) never active at any of the three exams. In addition, we calculated a cumulative activity score by assigning numeric values to each category at each exam (1 = regularly ≥ 2 h/week, 2 = regularly 1 h/week, 3 = irregularly ~ 1 h/week, 4 = no activity) and summing across Exams 1–3. This cumulative score ranged from 3 (high activity at all three exams: 1 + 1 + 1) to 12 (no activity at any exam: 4 + 4 + 4).

Occupational activity was self-reported at Exam 3 in four categories: (a) no significant physical labor, (b) light physical labor, (c) moderate

Table 3
Physical activity characteristics, obtained at Exam 1, Exam 2 and Exam 3.

	All (n = 360)	Women (n = 156)	Men (n = 204)	p
Physical activity (Exam 3)				0.055
≥2h, regularly	104 (28.9%)	44 (28.2%)	60 (29.4%)	
~1h, regularly	113 (31.4%)	58 (37.2%)	55 (27%)	
~1h, irregularly	51 (14.2%)	24 (15.4%)	27 (13.2%)	
no activities	92 (25.6%)	30 (19.2%)	62 (30.4%)	
Occupational activity (Exam 3)				0.014
heavy / moderate	105 (29.2%)	56 (35.9%)	49 (24%)	
light / not relevant	255 (70.8%)	100 (64.1%)	155 (76%)	
Walking activity (Exam 3)				0.387
>0.5 h daily	264 (73.3%)	118 (75.6%)	146 (71.6%)	
<=0.5 h	96 (26.7%)	38 (24.4%)	58 (28.4%)	
Cycling activity (Exam 3)				0.504
>0.5 h daily	111 (30.8%)	51 (32.7%)	60 (29.4%)	
<=0.5 h	249 (69.2%)	105 (67.3%)	144 (70.6%)	
Physical activity (longitudinal)*				
14 years ago (Exam 1)				0.152
≥1h, regularly	184 (51.1%)	73 (46.8%)	111 (54.4%)	
≤1h, irregularly	176 (48.9%)	83 (53.2%)	93 (45.6%)	
7 years ago (Exam 2)				0.777
≥1h, regularly	201 (58.4%)	86 (59.3%)	115 (57.8%)	
≤1h, irregularly	143 (41.6%)	59 (40.7%)	84 (42.2%)	
(≥1h, regularly over 14 years) (Exam 1 – Exam 3)				0.740
three/two times	191 (55.5%)	79 (54.5%)	112 (56.3%)	
one times/never	153 (44.5%)	66 (45.5%)	87 (43.7%)	
Summed over 14 years	7.4 (±2.8)	7.4 (±2.5)	7.4 (±3.1)	0.902

Data are given as number (percentage) or mean (± standard deviation). P-values are from chi-square-test or two-sided *t*-test.
*N = 16 subjects had missing data for Exam 2.

physical labor, or (d) heavy physical labor. For analysis, this was dichotomized into moderate/heavy labor vs. light/no physical labor.

Walking activity (at Exam 3) was reported as hours per day in four categories: (a) < 0.25 h, (b) 0.25–0.5 h, (c) 0.5–1 h, or (d) > 1h. We dichotomized walking time into > 0.5 h/day vs. ≤ 0.5 h/day. Cycling activity was recorded in the same manner and dichotomized similarly.

Covariates

Additional health-related variables were assessed at each KORA exam through standardized interviews and physical examinations. Smoking status was classified as never-smoker, ex-smoker, or current smoker (with pack-years calculated). Alcohol intake was measured using a validated recall method, calculating the average grams of alcohol per day based on self-reported beer, wine, sparkling wine, and spirits consumption over the previous week (separately for workdays and weekend) and then averaging.

Diabetes was defined as either a 2-hour plasma glucose ≥ 200 mg/dL on an oral glucose tolerance test, and/or a fasting glucose ≥ 125 mg/dL, and/or current use of glucose-lowering medication [14]. Hypertension was defined as systolic blood pressure ≥ 140 mmHg or diastolic ≥ 90 mmHg, or use of antihypertensive medication in individuals who reported a physician diagnosis of hypertension. Blood pressure was measured three times on the right arm of seated participants after at least five minutes of rest, with 3-minute intervals between measurements. An oscillometric digital monitor (Omron HEM-705CP, Omron Corp., Tokyo, Japan) with an appropriate cuff size was used. The mean of the second and third BP measurements was used for analysis. Current medication use (within the last 7 days) was recorded via a structured interview and by checking medication packages brought to the visit.

Weight and height were measured using calibrated scales and stadiometers (Seca GmbH & Co. KG, Hamburg, Germany) to the nearest 0.1 kg and 0.1 cm, respectively. Body mass index (BMI) was calculated as weight (kg) divided by height (m^2). Waist circumference (WC) was measured in centimeters to the nearest 0.1 cm using an inelastic multicolored measuring tape (Fa. Hoechstmass). WC was assessed midway between the lower rib margin and the iliac crest at the end of a gentle exhalation. The waist-to-hip ratio (WHR) was calculated as WC divided by hip circumference (HC). HC was measured at the widest part of the gluteal region, between the superior border of the iliac crest and the crotch.

Laboratory assays were performed on blood samples collected at the exams. Total cholesterol, LDL cholesterol, and HDL cholesterol were measured using enzymatic colorimetric assays. HbA1c was measured by a cation-exchange high-performance liquid chromatography photometric assays.

Statistical analyses

Continuous variables are presented as mean ± standard deviation (SD), and categorical variables as counts and percentages. Differences between women and men were tested using two-sided t-tests for continuous variables or chi-square tests for categorical variables. Pearson correlation coefficients were used to assess the relationships among the three strain parameters (GLS, GRS, GCS). A nonparametric trend test across ordered groups was applied to assess differences in strain values across physical activity categories (as displayed in box plots).

Intra-observer reliability was assessed using intraclass correlation coefficients (ICC) with 95% confidence intervals (CI) based on a two-way mixed-effects model with absolute agreement while inter-observer reliability was assessed using ICC based on a two-way random-effects model.

Multivariable linear regression models were adjusted for key confounders of the associations between physical activity (or inactivity) and LV strain parameters including age, sex, smoking status, and alcohol consumption. Other established cardiovascular risk factors such as obesity, hypertension, diabetes, and dyslipidemia were described but not included as confounders in our statistical models because they were considered as mediators for the relationship between physical activity and LV function.

Cross-sectional models evaluated activity reported at Exam 3, while longitudinal models evaluated activity patterns over time, as defined above. β-coefficients with CIs were calculated for the effect of physical inactivity on each strain outcome. The residuals of linear models were visually checked for normality. In addition, we performed a complementary longitudinal analysis using a repeated-measures generalized least squares regression model to relate multiple measurements of physical inactivity (over Exams 1–3) to the strain parameters measured at Exam 3. Potential effect modification by risk factors known to influence strain [13] was assessed by including interaction terms in the models; when a significant interaction was detected, results were presented stratified by the relevant subgroup. A complete-case analysis was performed, excluding participants with incomplete cardiac MR sequences for strain analysis at Exam 3 (n = 29) and further 16 participants with missing data on physical activity at Exam 2.

A two-sided p-value < 0.05 was considered statistically significant.

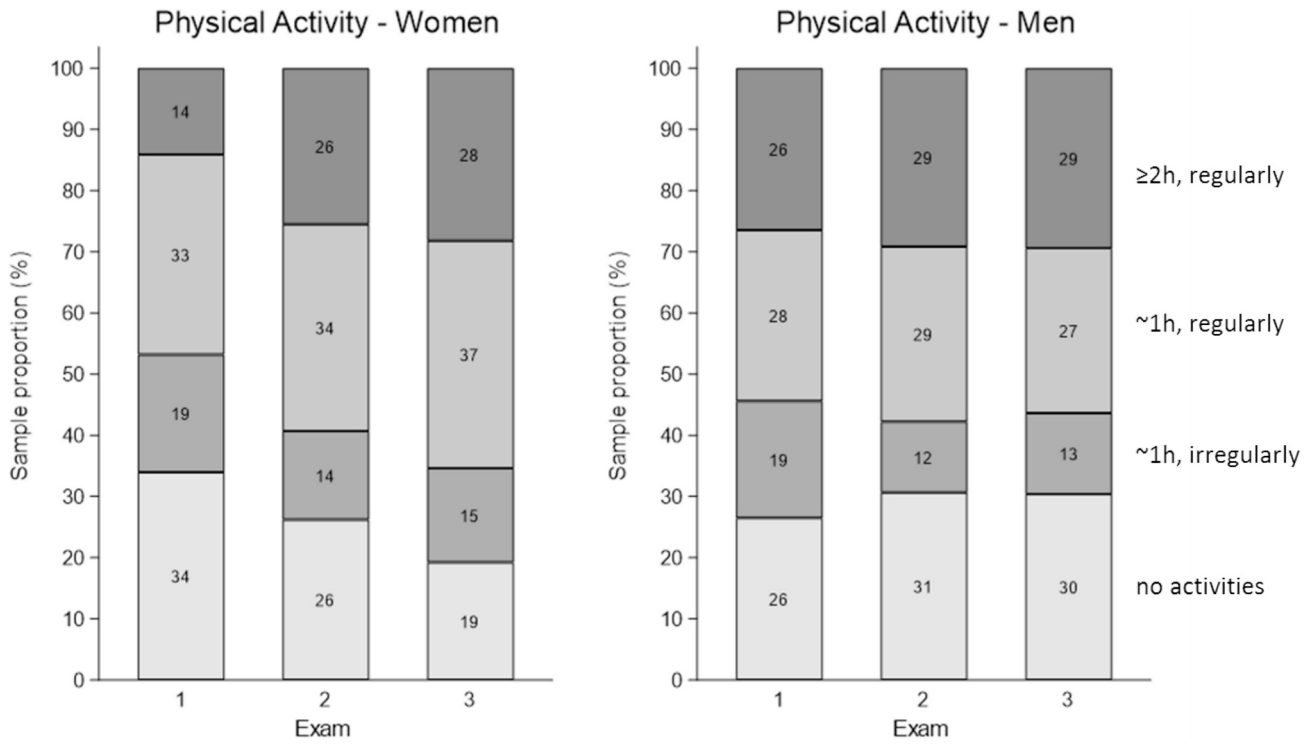

Fig. 2. Development of physical activity proportions over the three exams in women and men.

In addition, we used a Bonferroni-corrected significance level of $p < 0.017$ (0.05/3) for the primary analyses assessing the associations between physical activity and the three different strain parameters. All analyses were conducted using Stata 18.0 (StataCorp, College Station, TX, USA).

Results

Study participants (n = 360) had a mean age of 56.2 ± 9.2 years; 32.5% had hypertension and 12.5% had diabetes. In both women and men, approximately 20% of participants were current smokers, but men reported a higher average alcohol consumption than women ($p < 0.001$). Further cardiovascular risk characteristics of the Exam 3 subsample are presented in Table 1.

Intra-observer reliability was good for GLS (ICC = 0.79, 95% CI: 0.61 to 0.89) and GRS (ICC = 0.89, 95% CI: 0.78 to 0.94), and excellent for GCS (ICC = 0.93, 95% CI: 0.87 to 0.97). Inter-observer reliability was moderate but non-significant for GRS (ICC = 0.59, 95% CI: −0.08 to 0.85), and good for GCS (ICC = 0.70, 95% CI: 0.01 to 0.90) and GLS (ICC = 0.73, 95% CI: 0.51 to 0.86).

GRS was highly correlated with GCS ($r = 0.953$, $p < 0.001$) and moderately correlated with GLS ($r = 0.549$, $p < 0.001$). All three strain parameters were higher (indicating better myocardial deformation) in women than in men ($p < 0.001$ for all), as was the LV ejection fraction (Table 2). A total of 73 participants (21%) reported being physically inactive (≤1 h/week of irregular sports activity) at all three examination time points. In contrast, 121 participants (35%) reported regular physical activity (≥1 h/week) at all three exams. Overall, women and men had similar long-term exposure of physical activity patterns (Table 3), although the proportion of women who were regularly active increased over the 14-year period (Fig. 2).

Cross-sectional association of current physical activity with LV myocardial function

At Exam 3, lower levels of leisure-time physical activity were associated with lower values of all three LV strain parameters, with a larger effect on GRS and GCS ($p = 0.004$ for both) than on GLS ($p = 0.040$; Fig. 3, Panel C). Specifically, participants classified as physically inactive had significantly reduced GLS (β = –1.09%, 95% CI: –2.02 to –0.15; $p = 0.023$), GRS (β = –2.64%, 95% CI: –4.79 to –0.49; $p = 0.016$), and GCS (β = –0.90%, 95% CI: –1.60 to –0.20; $p = 0.012$) compared to physically active participants (Table 4, Fig. 4, Panel A). The two latter associations remained statistically significant using a Bonferroni-corrected p-values threshold of $p = 0.017$. By contrast, we found no significant associations between current occupational, walking, or cycling activity and any of the strain parameters.

We identified effect modification by both age and sex in these cross-sectional associations. Physical inactivity was more strongly associated with lower GLS in women (β = –1.59%, 95% CI: –3.05 to –0.13; $p = 0.033$, Table 4) than in men, and similarly more strongly associated with lower GLS in younger participants (≤56 years: β = –1.61%, 95% CI: –2.99 to –0.24; $p = 0.022$, Suppl. Table 1) than in those older than 56. In contrast, the association between inactivity and reduced GCS (and similarly GRS) was more pronounced in men (β = –1.08%, 95% CI: –2.03 to –0.14; $p = 0.024$, Table 4) than in women, and in participants > 56 years (β = –1.32%, 95% CI: –2.29 to –0.34; $p = 0.008$) than in younger individuals (Suppl. Table 1).

Association of remote and recent physical activity with current LV myocardial function

Remote physical inactivity at baseline (Exam 1) was associated with lower LV strain at Exam 3, including GLS (β = –0.70%, 95% CI: –1.39 to –0.01; $p = 0.048$), GRS (β = –1.97%, 95% CI: –3.54 to –0.39; $p = 0.015$), and GCS (β = –0.69%, 95% CI: –1.20 to –0.18; $p = 0.009$, Table 5). Participants who reported being inactive at two or all three exams over the 14-year period showed a greater reduction in strain measures at Exam 3: for example, those inactive at ≥ 2 exams had lower GRS (β = –2.09%, 95% CI: –3.71 to –0.47; $p = 0.012$) and lower GCS (β = –0.69%, 95% CI: –1.22 to –0.16; $p = 0.011$) compared to those who were inactive at only one or no exams. Again, most of these associations remained significant upon using a Bonferroni-corrected threshold of $p = 0.017$.

In interaction analyses of these longitudinal associations, sex (GRS, GCS) and age (GLS) were significant modifiers of the effect of remote inactivity on LV strain ($p < 0.05$ for interaction). Specifically, physical

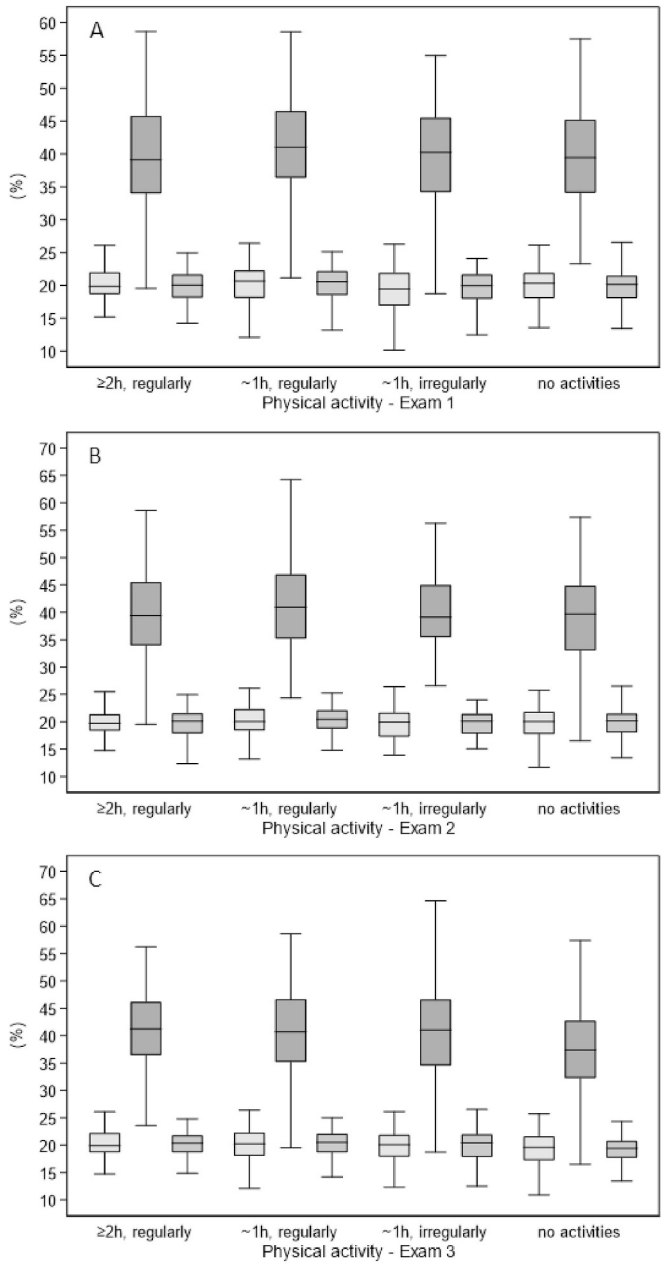

Fig. 3. Boxplots displaying differences of current longitudinal strain (light grey; p = 0.656, p = 0.586, p = 0.040), radial strain (dark grey; p = 0.382, p = 0.443, p = 0.004) and circumferential strain (medium grey; p = 0.457, p = 0.537, p = 0.004) between groups of physical activity measured during Exam 1 (Panel A), Exam 2 (Panel B) and Exam 3 (Panel C), respectively.

inactivity reported ~ 14 years prior (at Exam 1) was more strongly associated with lower GRS in men (β = –2.99%, 95% CI: –5.12 to –0.87; p = 0.006) than in women (Table 5) and with lower GLS in younger participants (≤56 years: β = –0.53%, 95% CI: –1.00 to –0.05; p = 0.030) than in older participants (Suppl. Table 2). The associations of cumulative long-term exposure of inactivity (across all three exams) with LV strain parameters are illustrated in Fig. 4, Panel B.

Discussion

We investigated the associations of current, recent, and remote physical activity with LV myocardial function, as assessed by MRI strain analysis, in a community-based cohort free of known cardiovascular events. Our principal findings were as follows: (a) current physical inactivity (lack of regular exercise) was cross-sectionally associated with lower values of all three LV strain parameters (GLS, GRS, and GCS); (b) self-reported inactivity in other domains (occupational, walking, and cycling) showed no significant association with LV strain measures; (c) physical inactivity measured up to 14 years before the MRI exam (at baseline) was also associated with decreased LV strain parameters; (d) the associations between physical inactivity and lower GRS/GCS were more pronounced in men and in older participants; and (e) the association between physical inactivity and lower GLS was primarily observed in women and in younger participants.

Physical activity and LV myocardial function

The link between physical inactivity and reduced LV myocardial function observed in our study is in good agreement with prior research. One large population-based study of over 57,000 middle-aged adults found an inverse association between leisure-time physical activity and impaired LV relaxation on echocardiography, with the relationship being stronger in men than in women [10]. In the ECHO-SOL study, which included 1,206 Latino participants, objectively measured physical activity (by accelerometer) was associated with more favorable LV parameters, including lower LV mass index, higher end-diastolic volume, and higher ejection fraction [9].

Cardiac MRI has also been used to examine exercise effects on the heart in epidemiological studies. In the Multi-Ethnic Study of Atherosclerosis, greater amounts of exercise (including team sports, dance, and moderate individual activities) were positively associated with MRI-derived LV mass, LV end-diastolic volume, and stroke volume [12]. In a recent analysis of the KORA cohort (from which our sample is drawn), physically inactive participants had lower LV ejection fraction, slower peak systolic ejection rate, and a lower early diastolic filling rate on MRI [11]. Our findings extend these results by using MRI-derived strain, an emerging measure of global LV function [13], to show consistent cross-sectional and longitudinal associations between physical inactivity and subtle impairments in myocardial performance.

While discussing "physical activity" as a general concept, it is important to distinguish between leisure-time and occupational physical activity, which can have opposite health effects. Leisure-time exercise is generally beneficial, whereas high levels of occupational physical activity have been linked to adverse health outcomes (the so-called physical activity paradox). Although methodological limitations (e.g., confounding by socioeconomic status) might partly explain this paradox, several well-conducted studies support it [16]. For example, greater occupational physical activity was associated with worse global LV function (lower echocardiographic ejection fraction) in a 25-year longitudinal cohort study [17]. Our study partially supports the physical activity paradox: we observed no significant association between self-reported occupational physical inactivity and LV strain, suggesting that differences in occupational activity (as captured in our data) did not translate into differences in subclinical LV function. Unlike leisure exercise, occupational activity levels were not associated with cardiac strain in our cohort.

Daily activities such as walking and cycling are known to reduce cardiovascular risk in both patient and general populations [18,19]. However, the present study did not detect an association between low levels of walking or bicycling activity and impaired subclinical LV function in cross-sectional analysis. This null finding might indicate that moderate everyday activities in this relatively healthy cohort were insufficient to influence LV strain, or it might reflect limitations in measuring these activities via self-report.

Sex differences in the association between inactivity and LV strain

We observed sex- and age-dependent patterns in the association between leisure-time physical inactivity and LV strain. These subgroup findings should be interpreted cautiously, as interaction and stratified analyses are more vulnerable to limited statistical power and residual confounding in modest sample sizes. Nevertheless, several non-mutually

Table 4
Association between current physical activity (Exam 3) and LV strain parameters.

Exam 3	Longitudinal Strain (%)		Radial Strain (%)		Circumferential Strain (%)	
All (n = 360)	β (95% CI)	p	β (95% CI)	p	β (95% CI)	p
Physical activity						
≥2h, regularly	Ref		Ref		Ref	
~1h, regularly	−0.65 (−1.55; 0.24)	0.152	−0.32 (−2.38; 1.74)	0.759	−0.12 (−0.79; 0.55)	0.725
~1h, irregularly	−0.91 (−2.10; 0.27)	0.129	−0.59 (−3.17; 1.98)	0.650	−0.21 (−1.05; 0.63)	0.622
no activities	−1.09 (−2.02; −0.15)	0.023	−2.64 (−4.79; −0.49)	0.016	−0.90 (−1.60; −0.20)	0.012
Occupational activity						
heavy / moderate	Ref		Ref		Ref	
light / not relevant	−0.01 (−0.79; 0.76)	0.970	1.15 (−0.61; 2.92)	0.198	0.34 (−0.24; 0.91)	0.250
Walking activity						
>0.5 h daily	Ref		Ref		Ref	
<=0.5 h	−0.51 (−1.30; 0.29)	0.211	−0.48 (−2.31; 1.35)	0.609	−0.17 (−0.76; 0.43)	0.586
Cycling activity						
>0.5 h daily	Ref		Ref		Ref	
<=0.5 h	0.02 (−0.75; 0.79)	0.960	0.14 (−1.59; 1.88)	0.871	0.10 (−0.46; 0.67)	0.717
Women (n = 156)						
Physical activity						
≥2h, regularly	Ref		Ref		Ref	
~1h, regularly	0.01 (−1.23; 1.26)	0.984	−0.40 (−3.34; 2.54)	0.787	0.01 (−0.89; 0.92)	0.974
~1h, irregularly	−0.17 (−1.75; 1.42)	0.836	3.50 (−0.20; 7.20)	0.063	1.25 (0.11; 2.39)	0.031
no activities	−1.59 (−3.05; −0.13)	0.033	−3.16 (−6.64; 0.32)	0.075	−0.70 (−1.77; 0.37)	0.197
Occupational activity						
heavy / moderate	Ref		Ref		Ref	
light / not relevant	−0.36 (−1.41; 0.69)	0.502	0.06 (−2.42; 2.54)	0.962	−0.09 (−0.85; 0.68)	0.825
Walking activity						
>0.5 h daily	Ref		Ref		Ref	
<=0.5 h	−0.97 (−2.13; 0.19)	0.101	−0.94 (−3.76; 1.89)	0.513	−0.18 (−1.05; 0.68)	0.675
Cycling activity						
>0.5 h daily	Ref		Ref		Ref	
<=0.5 h	−0.38 (−1.48; 0.71)	0.488	−1.68 (−4.26; 0.89)	0.199	−0.34 (−1.13; 0.45)	0.398
Men (n = 204)						
Physical activity						
≥2h, regularly	Ref		Ref		Ref	
~1h, regularly	−1.19 (−2.52; 0.14)	0.079	−0.01 (−2.88; 2.87)	0.996	−0.11 (−1.09; 0.86)	0.822
~1h, irregularly	−1.74 (−3.53; 0.04)	0.055	−4.36 (−7.92; −0.8)	0.017	−1.48 (−2.69; −0.27)	0.017
no activities	−0.95 (−2.23; 0.32)	0.141	−2.69 (−5.46; 0.09)	0.058	−1.08 (−2.03; −0.14)	0.024
Occupational activity						
heavy / moderate	Ref		Ref		Ref	
light / not relevant	0.32 (−0.83; 1.48)	0.582	2.23 (−0.31; 4.78)	0.085	0.74 (−0.12; 1.61)	0.091
Walking activity						
>0.5 h daily	Ref		Ref		Ref	
<=0.5 h	−0.16 (−1.28; 0.95)	0.772	−0.19 (−2.64; 2.25)	0.875	−0.17 (−1; 0.66)	0.692
Cycling activity						
>0.5 h daily	Ref		Ref		Ref	
<=0.5 h	0.39 (−0.72; 1.5)	0.492	1.58 (−0.8; 3.96)	0.193	0.47 (−0.34; 1.28)	0.253

β −coefficients are from linear regression models adjusted for age, sex, smoking status and alcohol consumption

exclusive mechanisms may contribute.

First, sex differences in myocardial deformation are well described in healthy populations, with women generally showing higher strain values than men across LV components, and evidence that age-related patterns may also differ by sex. Baseline differences in cardiac geometry, loading conditions, and myocardial material properties could therefore influence how inactivity relates to strain components (GLS vs GCS/GRS) [20–22].

Second, vascular mechanisms remain plausible. Estrogens modulate endothelial function and vasodilation, in part via nitric oxide pathways, and exercise training has repeatedly been shown to augment NO-dependent endothelial function [23–25]. In addition, menopause-related changes in estrogen signaling have been linked to alterations in vascular and myocardial function, including pathways affecting myocardial stiffness and diastolic properties. Such hormonal and vascular differences could contribute to sex- and age-related heterogeneity in how long-term exposure to inactivity associates with myocardial deformation, although our data cannot test these mechanisms directly [26,27].

Third, sex-specific cardiac adaptation to training (and potentially to inactivity) has been documented, with evidence that men and women can show different remodeling responses to exercise exposure across the life course [28,29]. Differential remodeling patterns might preferentially affect circumferential/radial mechanics versus longitudinal mechanics, but this remains speculative in the absence of longitudinal imaging.

Finally, measurement-related explanations should be considered. Physical activity was self-reported using broad categories, and misclassification may differ by sex or age. Together with limited power, this could amplify apparent subgroup differences. Accordingly, we view the sex- and age-specific results as hypothesis-generating and in need of confirmation in larger cohorts with objective activity measurement and serial imaging. Information on menopausal status and hormone therapy was not sufficiently detailed for meaningful classification and could therefore not be examined as potential contributors to sex- and age-specific associations.

Strengths and limitations

Strengths of our study include the well-characterized, population-based sample from the KORA cohort and the comprehensive, standardized assessment of cardiovascular risk factors and phenotypes. We employed advanced 3 T MRI and a quality-controlled analysis protocol to measure subclinical parameters of cardiac structure and function.

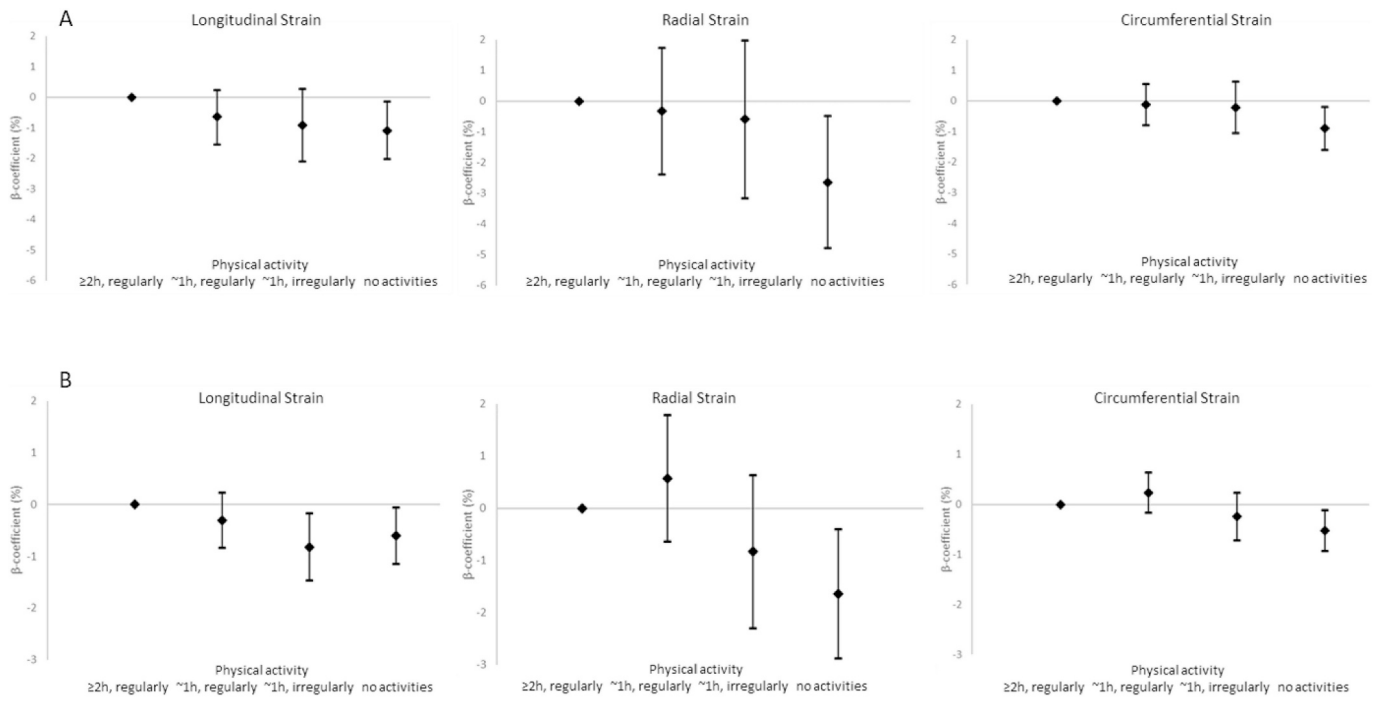

Fig. 4. Panel A: Cross-sectional associations between physical activity groups and left ventricular strain parameters during Exam 3; Panel B: Longitudinal associations between physical activity groups (during Exam 1–3) and left ventricular strain parameters displayed by β-coefficients with 95% confidence intervals (reference category = ≥2h regular active per week).

Table 5
Association between longitudinally measured physical activity (Exam 1, Exam 2 and Exam 3) and LV strain parameters.

Physical activity (longitudinal)	Longitudinal Strain (%)		Radial Strain (%)		Circumferential Strain (%)	
All (n = 360)	β (95% CI)	p	β (95% CI)	p	β (95% CI)	p
14 years ago (Exam 1)						
≥1h, regularly	Ref		Ref		Ref	
≤1h, irregularly	−0.70 (−1.39; −0.01)	0.048	−1.97 (−3.54; −0.39)	0.015	−0.69 (−1.20; −0.18)	0.009
7 years ago (Exam 2)						
≥1h, regularly	Ref		Ref		Ref	
≤1h, irregularly	−0.18 (−0.91; 0.55)	0.621	−1.34 (−2.99; 0.3)	0.109	−0.40 (−0.93; 0.14)	0.149
≥1h, regularly over 14 years (Exam 1 – Exam 3)						
three/two times	Ref		Ref		Ref	
one times/never	−0.53 (−1.24; 0.19)	0.151	−2.09 (−3.71; −0.47)	0.012	−0.69 (−1.22; −0.16)	0.011
Summed over 14 years	−0.09 (−0.22; 0.03)	0.148	−0.31 (−0.60; −0.03)	0.032	−0.10 (−0.20; −0.01)	0.030
Women (n = 156)						
14 years ago (Exam 1)						
≥1h, regularly	Ref		Ref		Ref	
≤1h, irregularly	−0.57 (−1.57; 0.43)	0.258	−0.59 (−2.97; 1.8)	0.628	−0.28 (−1.01; 0.46)	0.457
7 years ago (Exam 2)						
≥1h, regularly	Ref		Ref		Ref	
≤1h, irregularly	0.03 (−1.07; 1.12)	0.964	0.38 (−2.16; 2.93)	0.765	0.25 (−0.52; 1.03)	0.519
≥1h, regularly over 14 years (Exam 1 – Exam 3)						
three/two times	Ref		Ref		Ref	
one times/never	−0.59 (−1.65; 0.46)	0.268	0.06 (−2.45; 2.57)	0.964	0.18 (−0.58; 0.95)	0.641
Summed over 14 years	−0.12 (−0.33; 0.10)	0.286	−0.06 (−0.56; 0.43)	0.798	0 (−0.15; 0.15)	0.974
Men (n = 204)						
14 years ago (Exam 1)						
≥1h, regularly	Ref		Ref		Ref	
≤1h, irregularly	−0.81 (−1.79; 0.17)	0.104	−2.99 (−5.12; −0.87)	0.006	−1.00 (−1.72; −0.28)	0.007
7 years ago (Exam 2)						
≥1h, regularly	Ref		Ref		Ref	
≤1h, irregularly	−0.35 (−1.37; 0.67)	0.501	−2.50 (−4.70; −0.30)	0.026	−0.83 (−1.58; −0.08)	0.031
≥1h, regularly over 14 years (Exam 1 – Exam 3)						
three/two times	Ref		Ref		Ref	
one times/never	−0.54 (−1.57; 0.49)	0.302	−3.77 (−5.94; −1.61)	0.001	−1.36 (−2.09; −0.62)	<0.001
Summed over 14 years	−0.08 (−0.24; 0.08)	0.314	−0.43 (−0.79; −0.08)	0.018	−0.15 (−0.27; −0.03)	0.014

β −coefficients are from linear regression models adjusted for age, sex, smoking status and alcohol consumption

Another notable strength is the use of physical activity data not only from the time of MRI (Exam 3) but also from examinations 7 and 14

years prior, allowing us to evaluate associations with long-term physical activity patterns.

Several limitations merit consideration. First, LV strain was assessed only once (Exam 3), so our analyses reflect associations with long-term activity patterns rather than temporal change in myocardial function, and causal interpretation is limited. In particular, reverse causation cannot be excluded, as subclinical myocardial impairment may itself have reduced physical activity before imaging. Second, the MRI substudy included only Exam 3 participants who were eligible for MRI and free of clinically overt CVD. This may have introduced a healthy survivor bias, a form of selection bias. Therefore, our findings mainly apply to individuals without clinical CVD. An analysis using sampling weights (to better reflect the full cohort) showed no major differences in cardiac measures and their associations with cardiovascular risk factors compared to the unweighted analysis [30], but some degree of selection bias cannot be entirely excluded. Third, physical activity was assessed using a self-reported questionnaire. Objective, sensor-based measures of activity (e.g., accelerometers) were not available at the time of data collection, so some misclassification of activity levels is likely. Fourth, our sample consisted predominantly of individuals of European ancestry from one region in Germany, so the generalizability of these findings to other ethnic groups or regions is uncertain. Fifth, although we adjusted for key covariates, residual confounding by unmeasured lifestyle or health factors (e.g., diet, occupational factors, genetic predispositions) cannot be ruled out.

Finally, the absolute strain differences associated with physical inactivity in our cohort were modest, in the order of approximately 1 percentage point for GLS and GCS and around 2–3 percentage points for GRS. While statistically significant after Bonferroni-correction for multiple testing, these differences are small in absolute terms and may not translate to clinically meaningful dysfunction in the absence of other risk factors. Several considerations are relevant when interpreting effects of this magnitude. Absolute feature-tracking strain values vary considerably across software platforms and analysis protocols, which precludes direct comparison of absolute values between studies; our estimates, however, derive from within-study contrasts using a single, standardized analysis pipeline. With respect to measurement reliability, GCS, the most reproducible parameter in our analysis and in prior reproducibility studies, showed the most consistent associations, whereas GRS, the least reproducible parameter, should be interpreted more cautiously [31–33]. Although, individual-level measurement variability is non-trivial, group-level mean differences can be estimated reliably in a sample of this size. Finally, while small strain differences have demonstrated prognostic relevance in clinical populations [34,35], the prognostic significance of subclinical, population-level differences of this magnitude in individuals without overt CVD remains to be established. We therefore interpret our findings as population-level, hypothesis-generating associations rather than evidence of clinically manifest myocardial dysfunction.

Perspectives

Our findings indicate that repeated reports of physical inactivity over a 14-year period were associated with less favourable subclinical cardiac function, as reflected by lower LV strain, measured at the end of the 14-year period (at Exam 3). While this observation is consistent with the concept that cumulative exposure to physical activity shapes cardiac (dys)function, the one-time assessment of myocardial function precludes conclusions about longitudinal deterioration in cardiac function. Nevertheless, the observations support the hypothesis that sustained engagement in physical activity may be relevant for myocardial function. From a public health perspective, promoting physical activity across the lifespan remains an important strategy to support cardiovascular health.

Conclusion

In this subsample of the population-based KORA cohort without overt cardiovascular disease, repeated self-reports of leisure-time physical inactivity over 14 years were associated with lower subclinical cardiac function at the end of the 14-year period (Exam 3), as reflected by lower MRI feature-tracking derived LV strain parameters. This observation suggests that sustained inactivity over 1 ½ decades may be linked to subtle alterations in myocardial deformation later in life, which represent important precursors for clinical cardiac disease. As an observational study based on self-reported activity, our analysis establishes associations rather than causation. Longitudinal studies employing objective measures of physical activity alongside repeated imaging assessments are warranted to further explore the relation between physical activity and changes in cardiac structure and function over time.

CRediT authorship contribution statement

Philipp Franke: Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Thomas Geyer:** Writing – review & editing, Validation, Software, Methodology, Formal analysis. **Sophia Stöcklein:** Writing – review & editing, Supervision, Resources, Funding acquisition. **Olaf Dietrich:** Writing – review & editing, Software, Resources, Methodology. **Bernd J. Wintersperger:** Writing – review & editing, Supervision, Software, Resources, Methodology. **Susanne Rospleszcz:** Writing – review & editing, Project administration, Methodology, Data curation. **Christopher L. Schlett:** Writing – review & editing, Project administration, Methodology, Funding acquisition. **Fabian Bamberg:** Writing – review & editing, Resources, Project administration, Methodology, Funding acquisition. **Annette Peters:** Writing – review & editing, Resources, Project administration, Methodology, Funding acquisition. **Wolfgang Lieb:** Writing – review & editing, Supervision, Resources, Conceptualization. **Roberto Lorbeer:** Writing – original draft, Visualization, Supervision, Project administration, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ejrad.2026.113091.

References

[1] A.N. Nowbar, M. Gitto, J.P. Howard, D.P. Francis, R. Al-Lamee, Mortality from Ischemic Heart Disease, Circ. Cardiovasc. Qual. Outcomes 12 (2019) e005375.
[2] Mensah GA, Fuster V, Murray CJL, Roth GA, Global Burden of Cardiovascular D, Risks C. Global Burden of Cardiovascular Diseases and Risks, 1990-202J Am Coll Cardiol 2023;82:2350-2473.
[3] S. Zhao, Z. Zhang, Q. Long, Y. Ma, X. Lian, Y. Yang, W. Gao, Z. Chen, L. Wang, Association between Time of Day of Sports-Related Physical activity and the Onset of Acute Myocardial Infarction in a Chinese Population, PLoS One 11 (2016) e0146472.
[4] S. Ghozy, A.H. Zayan, A.E. El-Qushayri, K.E. Parker, J. Varney, K.M. Kallmes, S. Morsy, A.S. Abbas, J.D.B. Diestro, A.A. Dmytriw, J. Shah, A.E. Hassan, S.M. S. Islam, Physical activity level and stroke risk in US population: a matched case-control study of 102,578 individuals, Ann. Clin. Transl. Neurol. 9 (2022) 264–275.
[5] S.M. Kang, S.H. Kim, K.D. Han, N.J. Paik, W.S. Kim, Physical activity after ischemic stroke and its association with adverse outcomes: a nationwide population-based cohort study, Top. Stroke Rehabil. 28 (2021) 170–180.
[6] Y. Gerber, V. Myers, U. Goldbourt, Y. Benyamini, M. Scheinowitz, Y. Drory, Long-term trajectory of leisure time physical activity and survival after first myocardial infarction: a population-based cohort study, Eur. J. Epidemiol. 26 (2011) 109–116.
[7] C.W. Tsao, P.N. Gona, C.J. Salton, M.L. Chuang, D. Levy, W.J. Manning, C. J. O'Donnell, Left Ventricular Structure and risk of Cardiovascular events: a

Framingham Heart Study Cardiac magnetic Resonance Study, J. Am. Heart Assoc. 4 (2015) e002188.
[8] C.C. Nwabuo, H.T. Moreira, H.D. Vasconcellos, N. Mewton, A. Opdahl, K. O. Ogunyankin, B. Ambale-Venkatesh, P.J. Schreiner, A.A.C. Armstrong, C. E. Lewis, D.R. Jacobs, D. Lloyd-Jones, S.S. Gidding, J.A.C. Lima, Left ventricular global function index predicts incident heart failure and cardiovascular disease in young adults: the coronary artery risk development in young adults (CARDIA) study, Eur. Heart J. Cardiovasc. Imaging 20 (2019) 533–540.
[9] A.E. Berdy, B. Upadhya, S. Ponce, K. Swett, R.B. Stacey, R. Kaplan, P.M. Vasquez, Q. Qi, N. Schneiderman, B.E. Hurwitz, M.L. Daviglus, M. Kansal, K.R. Evenson, C. J. Rodriguez, Associations between physical activity, sedentary behaviour and left ventricular structure and function from the Echocardiographic Study of Latinos (ECHO-SOL). Open, Heart 8 (2021).
[10] S. Ryu, Y. Chang, J. Kang, K.E. Yun, H.S. Jung, C.W. Kim, J. Cho, J.A. Lima, K. C. Sung, H. Shin, E. Guallar, Physical activity and impaired left ventricular relaxation in middle aged adults, Sci. Rep. 8 (2018) 12461.
[11] A. Schafnitzel, R. Lorbeer, C. Bayerl, H. Patscheider, S.D. Auweter, C. Meisinger, M. Heier, B. Ertl-Wagner, M. Reiser, A. Peters, F. Bamberg, H. Hetterich, Association of smoking and physical inactivity with MRI derived changes in cardiac function and structure in cardiovascular healthy subjects, Sci. Rep. 9 (2019) 18616.
[12] S.R. Heckbert, W. Post, G.D. Pearson, D.K. Arnett, A.S. Gomes, M. Jerosch-Herold, W.G. Hundley, J.A. Lima, D.A. Bluemke, Traditional cardiovascular risk factors in relation to left ventricular mass, volume, and systolic function by cardiac magnetic resonance imaging: the Multiethnic Study of Atherosclerosis, J. Am. Coll. Cardiol. 48 (2006) 2285–2292.
[13] T. Zitzelsberger, A. Scholz, H. Hetterich, R. Lorbeer, F. Bamberg, S.D. Auweter, M. Heier, C. Meisinger, W. Rathmann, K. Nikolaou, M.F. Reiser, A. Peters, C. L. Schlett, Magnetic Resonance-based Assessment of Myocardial 2-Dimensional Strain using Feature Tracking: Association with Cardiovascular Risk Factors in a Population-based Cohort Free of Cardiovascular Disease, J. Thorac. Imaging 35 (2020) 49–55.
[14] F. Bamberg, H. Hetterich, S. Rospleszcz, R. Lorbeer, S.D. Auweter, C.L. Schlett, A. Schafnitzel, C. Bayerl, A. Schindler, T. Saam, K. Muller-Peltzer, W. Sommer, T. Zitzelsberger, J. Machann, M. Ingrisch, S. Selder, W. Rathmann, M. Heier, B. Linkohr, C. Meisinger, C. Weber, B. Ertl-Wagner, S. Massberg, M.F. Reiser, A. Peters, Subclinical Disease Burden as Assessed by Whole-Body MRI in Subjects with Prediabetes, Subjects with Diabetes, and Normal Control Subjects from the General Population: the KORA-MRI Study, Diabetes 66 (2017) 158–169.
[15] M. Rabel, C. Meisinger, A. Peters, R. Holle, M. Laxy, The longitudinal association between change in physical activity, weight, and health-related quality of life: results from the population-based KORA S4/F4/FF4 cohort study, PLoS One 12 (2017) e0185205.
[16] N. Gupta, S. Dencker-Larsen, C. Lund Rasmussen, D. McGregor, C.D.N. Rasmussen, S.V. Thorsen, M.B. Jorgensen, S. Chastin, A. Holtermann, The physical activity paradox revisited: a prospective study on compositional accelerometer data and long-term sickness absence, Int. J. Behav. Nutr. Phys. Act. 17 (2020) 93.
[17] T.D. Quinn, A. Lane, K.P. Gabriel, B. Sternfeld, D.R. Jacobs Jr., P. Smith, G. B. Barone, Associations between Occupational Physical activity and Left Ventricular Structure and Function over 25 Years in CARDIA. Eur, J Prev Cardiol (2023).
[18] A.E. Paluch, S. Bajpai, M. Ballin, D.R. Bassett, T.W. Buford, M.R. Carnethon, A. Chernofsky, E.E. Dooley, U. Ekelund, K.R. Evenson, D.A. Galuska, B.J. Jefferis, L. Kong, W.E. Kraus, M.G. Larson, I.M. Lee, C.E. Matthews, R.L. Newton Jr., A. Nordstrom, P. Nordstrom, P. Palta, A.V. Patel, K. Pettee Gabriel, C.F. Pieper, L. Pompeii, E. Rees-Punia, N.L. Spartano, R.S. Vasan, P.H. Whincup, S. Yang, J. E. Fulton, Steps for Health C. prospective Association of Daily Steps with Cardiovascular Disease: a Harmonized Meta-Analysis, Circulation 147 (2023) 122–131.
[19] K. Blond, M.K. Jensen, M.G. Rasmussen, K. Overvad, A. Tjonneland, L. Ostergaard, A. Grontved, Prospective Study of Bicycling and risk of Coronary Heart Disease in danish men and Women, Circulation 134 (2016) 1409–1411.
[20] F. Andre, H. Steen, P. Matheis, M. Westkott, K. Breuninger, Y. Sander, R. Kammerer, C. Galuschky, E. Giannitsis, G. Korosoglou, H.A. Katus, S.J. Buss, Age- and gender-related normal left ventricular deformation assessed by cardiovascular magnetic resonance feature tracking, J. Cardiovasc. Magn. Reson. 17 (2015) 25.
[21] K. Mangion, N.M.M. Burke, C. McComb, D. Carrick, R. Woodward, C. Berry, Feature-tracking myocardial strain in healthy adults- a magnetic resonance study at 3.0 tesla, Sci. Rep. 9 (2019) 3239.
[22] R. Pillai, L. Zhang, K. Peters, V. Jha, C.J. O'Donnell, W.J. Manning, C.W. Tsao, Age- and sex-differences and reference values for ventricular strain by cardiovascular magnetic resonance imaging in adults without cardiovascular disease or cardiovascular disease risk factors, J. Cardiovasc. Magn. Reson. 27 (2025) 101902.
[23] K.L. Chambliss, P.W. Shaul, Estrogen modulation of endothelial nitric oxide synthase, Endocr. Rev. 23 (2002) 665–686.
[24] D.J. Green, A. Maiorana, G. O'Driscoll, R. Taylor, Effect of exercise training on endothelium-derived nitric oxide function in humans, J. Physiol. 561 (2004) 1–25.
[25] R. Hambrecht, V. Adams, S. Erbs, A. Linke, N. Krankel, Y. Shu, Y. Baither, S. Gielen, H. Thiele, J.F. Gummert, F.W. Mohr, G. Schuler, Regular physical activity improves endothelial function in patients with coronary artery disease by increasing phosphorylation of endothelial nitric oxide synthase, Circulation 107 (2003) 3152–3158.
[26] P.Z. Maslov, J.K. Kim, E. Argulian, A. Ahmadi, N. Narula, M. Singh, J. Bax, J. Narula, Is Cardiac Diastolic Dysfunction a Part of Post-Menopausal Syndrome? JACC Heart Fail 7 (2019) 192–203.
[27] A.R. Sabbatini, G. Kararigas, Menopause-Related Estrogen Decrease and the Pathogenesis of HFpEF: JACC Review Topic of the Week, J. Am. Coll. Cardiol. 75 (2020) 1074–1082.
[28] Z. Lasocka-Koriat, Z. Lewicka-Potocka, A. Kaleta-Duss, A. Siekierzycka, L. Kalinowski, E. Lewicka, A. Dabrowska-Kugacka, Differences in cardiac adaptation to exercise in male and female athletes assessed by noninvasive techniques: a state-of-the-art review, Am. J. Physiol. Heart Circ. Physiol. 326 (2024) H1065–H1079.
[29] B.J. Petek, E.H. Chung, J.H. Kim, R. Lampert, B.D. Levine, D. Phelan, A. Danielian, P.N. Dean, E.H. Dineen, A.B. Fernandez, M. Husaini, S. Krishnan, A.B. Shah, K. M. Stewart, M.M. Wasfy, Impact of sex on Cardiovascular Adaptations to Exercise: JACC Review Topic of the Week, J. Am. Coll. Cardiol. 82 (2023) 1030–1038.
[30] R. Lorbeer, S. Rospleszcz, C.L. Schlett, S.D. Rado, B. Thorand, C. Meisinger, W. Rathmann, M. Heier, R.S. Vasan, F. Bamberg, A. Peters, W. Lieb, Association of antecedent cardiovascular risk factor levels and trajectories with cardiovascular magnetic resonance-derived cardiac function and structure, J. Cardiovasc. Magn. Reson. 23 (2021) 2.
[31] M. Barreiro-Perez, D. Curione, R. Symons, P. Claus, J.U. Voigt;, J. Bogaert, Left ventricular global myocardial strain assessment comparing the reproducibility of four commercially available CMR-feature tracking algorithms, Eur. Radiol. 28 (2018) 5137–5147.
[32] E. Cavus, K. Muellerleile, S. Schellert, J. Schneider, E. Tahir, C. Chevalier, C. Jahnke, U.K. Radunski, G. Adam, P. Kirchhof, S. Blankenberg, G.K. Lund, M. Avanesov, M. Patten, CMR feature tracking strain patterns and their association with circulating cardiac biomarkers in patients with hypertrophic cardiomyopathy, Clin. Res. Cardiol. 110 (2021) 1757–1769.
[33] P. Pierpaolo, S. Rolf, B.P. Manuel, C. Davide, T. Dresselaers, P. Claus, J. Bogaert, Left ventricular global myocardial strain assessment: are CMR feature-tracking algorithms useful in the clinical setting? Radiol. Med. 125 (2020) 444–450.
[34] D.A. Morris, C.L. Hung, T. Biering-Sorensen, T. Kuznetsova, E. Donal, W. Kosmala, M. Takeuchi, R. Lang, M. Tadic, C.Y. Ma, E. Belyavskiy, H. Dreger, M. Schneider-Reigbert, A. Frydas, Prognostic Relevance and lower Limit of the Reference Range of Left Ventricular Global Longitudinal Strain: a Clinical Validation Study, JACC Cardiovasc. Imaging 18 (2025) 525–536.
[35] M. Saito, F. Khan, T. Stoklosa, A. Iannaccone, K. Negishi, T.H. Marwick, Prognostic Implications of LV Strain Risk score in Asymptomatic patients with Hypertensive Heart Disease, JACC Cardiovasc. Imaging 9 (2016) 911–921.