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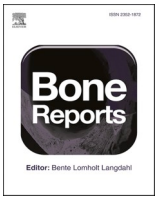

Association of daily physical activity and bone microarchitecture in young adults with type 1 diabetes — A pilot exploratory study

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ABSTRACT

Purpose: Physical activity (PA) is an important determinant of skeletal health. In young adults with type 1 diabetes (T1D) fracture risk is increased, yet few studies have examined the PA and bone health relationship. Therefore, this pilot cross-sectional study characterized PA levels and their association with bone parameters measured by high resolution peripheral quantitative computed tomography (HR-pQCT) in young adults with T1D.

Methods: HR-pQCT (Xtreme CTII) was used to measure bone outcomes at the distal tibia and radius, and accelerometery (ActiGraph GT3X) recorded daily minutes of light and moderate-vigorous physical activity (MVPA). Quadratic regression analyses were conducted with a p-value ≤ 0.05 considered significant.

Results: PA data from 19 young adults (23.1 ± 1.9 years) with T1D was analyzed. Over half (63 %) of participants completed ≥150 min of MVPA per week, however, most measured activity time per day (57 %) was spent in sedentary pursuits. Significant non-linear associations were found between the duration of MVPA and several trabecular bone parameters at the tibia.

Conclusions: In young adults with T1D, MVPA may have site specific (tibia) and compartment specific (trabecular) non-linear associations with bone. Further studies should confirm these findings, which may help inform evidence-based exercise recommendations to optimize bone health in young adults with T1D.

1. Introduction

Type 1 diabetes (T1D) is an autoimmune disease associated with multiple co-morbidities and long-term multi-system consequences (Akil et al., 2021). One such complication is poor skeletal health; reduced bone microarchitecture, as well as increased fracture risk are well documented in individuals with longstanding T1D (Shah et al., 2015; Janghorbani et al., 2007). Impaired bone health in T1D may result from multiple factors such as poor metabolic control, hyperinsulinemia, autoimmune inflammation, vitamin D deficiency, and physical inactivity (Zhukouskaya et al., 2014).

Fracture risk in adults is largely dependent on normal bone mass accrual during childhood and adolescence (Leonard, 2007) and physical activity (PA) positively impacts bone development during this time (Proia et al., 2021). In T1D, there has been extensive research assessing the impact of PA on outcomes including increased insulin sensitivity, glycaemic control, decreased blood pressure, improved cardiovascular fitness and the blood lipid profile (Cannata et al., 2020; Chang et al., 2023; García-Hermoso et al., 2023; Aljawarneh et al., 2019; Wu et al., 2019). However, despite the importance of PA on bone health, there are a limited number of studies examining the PA-skeletal health relationship in adolescents/young adults with T1D, and published study results report mixed conclusions (Gil-Díaz et al., 2019; Joshi et al., 2013; Maggio et al., 2010; Zheng et al., 2024). For example, Joshi et al. examined the association of PA (measured by the International PA Questionnaire) and bone (measured by dual energy X-ray absorptiometry; DXA), and found that PA was positively correlated with bone mineral density (BMD) Z-score at the total body and lumbar spine sites in young adults with T1D (Joshi et al., 2013). However, in another study investigating children and adolescents (N = 27) with T1D, PA (as measured by accelerometry) was lower in those with T1D vs. healthy controls, but there was no difference in total body, lumbar spine, or

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femoral neck BMD, and there was no significant associations between PA and total body BMD in those with T1D (Maggio et al., 2010). In a recent study by Zheng et al. (2024) children with T1D had trabecular bone deficits at both the radius and tibia (measured by high-resolution peripheral quantitative computed tomography; HR-pQCT) but higher cortical measures compared to typically developing peers. PA participation was lower in children with T1D when measured via questionnaire, but when measured by accelerometry PA was similar between both groups. Only PA as determined by questionnaire was a mediator of the presence of T1D and trabecular number difference at the radius (Zheng et al., 2024).

One reason for these variable findings might be that prior studies have primarily used DXA to measure bone outcomes. While DXA is an excellent tool that discriminates fracture risk in many groups including postmenopausal women (DeSapri and Brook, 2020), DXA is a 2-dimensional planar instrument which does not capture cortical and trabecular microarchitecture nor bone strength (i.e. load carrying capacity) which can predict fracture risk independently (Nishiyama and Shane, 2013). By contrast, HR-pQCT provides measurement of bone microarchitecture, volumetric BMD (g/cm^3), as well as strength (Mata-Mbemba et al., 2019). However, there are few studies that have examined bone by HR-pQCT in individuals living with T1D (Zheng et al., 2024; Sochett et al., 2023; Zheng et al., 2022). In addition, prior studies (Joshi et al., 2013; Maggio et al., 2010) have used multiple methodologies to measure PA including survey assessments that make comparison difficult (Zheng et al., 2024; Prince et al., 2008; Ferrari et al., 2007). Accelerometry is a methodology that provides quantitative data regarding intensity, duration, and frequency of daily activity, and does not rely on PA recall like many survey-based measures (Sylvia et al., 2014; Melanson Jr. et al., 1996). To date, only one study has examined PA (measured by survey and accelerometry) and the association with bone outcomes (measured by HR-pQCT) in children with T1D (mean age ~12 years) (Zheng et al., 2024), however, there are currently no published studies reporting this association in young adults with T1D.

Therefore, the current study aimed to address these limitations by: 1) characterizing PA levels using accelerometry, and 2) evaluating the relationship between HR-pQCT measures and accelerometry measured PA in young adults with T1D. It was hypothesized that young adults with T1D would not be meeting current PA guidelines (Ross et al., 2020) and that several HR-pQCT bone outcomes would be associated with PA.

2. Material and methods

2.1. Study population and design

Participants were recruited from a 4-year prospective, observational study in T1D young adults evaluating the cardio-renal bone health profile at the Hospital for Sick Children (SickKids) in Toronto, Canada (Levin et al., 2018). Inclusion criteria for this cross-sectional analysis at the mid-point study visit (2021) were a confirmed diagnosis of T1D using the Canadian Clinical Practice Guidelines and completion of the HR-pQCT and accelerometry assessment. Exclusion criteria was the presence of any significant co-morbidities, a history of 3 or more long bone fractures, and chronic use of medications that negatively impact bone health. The study was approved by the SickKids Research Ethics Board (REB File Number #100055749) and participants provided informed consent in accordance with the Declaration of Helsinki.

2.2. Study procedures

Demographic and clinical data were collected from each participant by a trained research team member, including age, sex, and relevant diabetes details. Lifetime long bone fracture history and alcohol and smoking status were obtained using a questionnaire and the TAPS Tool, respectively (Adam et al., 2019). Height (cm) was measured at the study visit with a wall mounted digital stadiometer, and weight (kg) was measured using an electronic scale. Body mass index (BMI) was calculated as weight divided by height in meters squared. BMI was categorized as underweight (<18.5 kg/m^2), normal weight (18.5–24.9 kg/m^2), overweight (25.0–29.9 kg/m^2), and obese (30.0–34.9 kg/m^2) (Weir and Jan, 2024). Venous blood was drawn after a minimum 3 h fasting period in a sitting position for hemoglobin A1C and measured at the Department of Pediatric Laboratory Medicine at SickKids contemporaneous with the HR-pQCT and accelerometry assessment.

2.3. Accelerometery

Quantitative PA data was obtained through accelerometry (GT3X accelerometer, ActiGraph LLC, Pensacola, FL). Participants were instructed to continue with normal routines, and to wear the accelerometer on a belt around the waist during waking hours for 7 consecutive days only removing the device while swimming, bathing, or sleeping. The accelerometer was deployed at the same time as the HR-pQCT imaging, with the accelerometer set to record data at 30 Hz (Clevenger et al., 2022), using an epoch period of 15 s (Government of Canada SC, 2014; Quante et al., 2015). Accelerometer data were downloaded using ActiLife software (version 6.13.4, Actigraph LLC) and processed to generate outcome variables. Non-wear time was defined as a period of 60 min or longer of unaccounted for continuous zero values (Chinapaw et al., 2014). A modified Freedson algorithm was used to determine counts per minute (CPM) PA intensity cut-points (Freedson et al., 1998). A PA minute was categorized as sedentary (<100 CPM), light (100–1951 CPM) moderate (1952–5724 CPM) and vigorous activity (≥5725 CPM) (Freedson et al., 1998). For a participant's data to be included in the present analysis, a minimum of 4 valid wear days were required (Trost et al., 2005). Since the research group was examining activity in a chronic disease population, we anticipated that individuals might be inactive for larger periods of times, therefore, a total minimum wear time was not defined. Outcome measures included mean time spent engaged in sedentary, light, moderate, vigorous, and moderate-vigorous PA (MVPA) in minutes per day.

2.4. HR-pQCT imaging and analysis

The non-dominant radius and tibia were scanned on a HR-pQCT scanner (XtremeCT II; Scanco Medical AG, Brüttisellen, Switzerland), as previously described (Sochett et al., 2023). Briefly, an anteroposterior scout projection of the scan site was acquired for positioning of the tomographic acquisition. A reference line was placed on the plateau of the distal radius or distal tibia. The scan started 9 mm and 22 mm for the radius and tibia, respectively, from the reference in the proximal direction, and spanned 10.2 mm in length. Images were reconstructed using an isotropic resolution of 60.7 μm (Whittier et al., 2020a), thus resulting in a stack of 168 parallel HR-pQCT slices (Whittier et al., 2020a; Whittier et al., 2020b). All acquired scans were visually scored for presence and severity of motion artifact using the 5-level motion grading scale (Whittier et al., 2020a). Separation of cortical and trabecular regions was done automatically, and borders were thereafter inspected and corrected manually by the operator, if necessary (Burghardt et al., 2010). Standard morphologic analysis was used to measure volumetric BMD for total (TtBMD; mg HA/cm^3) and trabecular (TbBMD; mg HA/cm^3) bone, as well as trabecular number (TbN; mm^{-1}), separation (TbSp; mm), and thickness (TbTh; mm) (Boutroy et al., 2005). An automated segmentation algorithm was used to obtain total and cortical cross-sectional areas (TtAr, CtAr, mm^2), cortical volumetric BMD (CtBMD; mg HA/cm^3), cortical thickness (CtTh; mm), and cortical porosity (CtPo; %) (Burghardt et al., 2010; Buie et al., 2007). Finite element analysis was applied to HR-pQCT images to estimate t bone strength using the μFE pipeline implemented on the scanner software (Pistoia et al., 2002). In brief, the μFE models were generated by a direct voxel conversion approach based on the segmentation of the standard evaluation. Linear elastic material properties (Young's modulus E = 10

GPa, Poisson's ratio $\nu = 0.3$) were assigned to all elements. Failure load was defined according to the Pistoia criterion to occur when a minimum of 2 % of the tissue volume is loaded beyond a critical strain of 0.7 % (Pistoia et al., 2002). Scans were then reviewed for a second time by the nuclear medicine radiologists for the following image quality measures: correct placement of reference line, presence of motion artifact, optimal periosteal contour placement, and for any visible pathology or artifact of the trabeculae and cortex. All scans that met the image quality measures were included in the analysis.

2.5. Statistical analysis

Descriptive statistics were used to calculate demographic, clinical and laboratory test variables. Mean with standard deviation (SD) were provided for continuous variables. Frequency and proportions were calculated for categorical variables. HR-pQCT parameters expressed as *Z*-scores were generated from an adult normative HR-pQCT database covering both sexes and the adult age span at the distal radius and distal tibia (Whittier et al., 2020a; Whittier et al., 2020b). The age, weight, and BMI of subjects was similar to those healthy controls in the age range of 20–30 years in the normative database (Whittier et al., 2020b). *Z*-scores were chosen rather than absolute values for several reasons; they are commonly used for assessment in the young adult population and *Z*-scores obviates the need for adjustments for age and sex (Sochett et al., 2023).

Scatter plots were generated and given that these plots suggested a non-linear relationship between physical activity and bone parameters, curve fitting was then undertaken using linear regression analyses with a polynomial term, specifically quadratic. Quadratic analysis was chosen because R^2 values for this model were consistently higher than the values for linear regression. The linear regression analyses are also provided. The beta co-efficient of the fitted quadratic regressions were used to describe the nature of the relationship (direction and steepness), as well to estimate the daily minutes of light PA and MVPA. For MVPA, the turning point that occurred in the relevant bone parameters (maximum or minimum) was reported. A p-value ≤ 0.05 was considered statistically significant. All analyses were performed using SAS 9.4 software (SAS Institute Inc., Cary, N.C., USA).

3. Results

3.1. Clinical characteristics

A total of 20 individuals with T1D completed the accelerometry and HR-pQCT assessments, with one participant's HR-pQCT scan withdrawn due to poor visualization of bone, therefore, 19 participants were included in the analyses. The demographic and clinical characteristics of the cohort stratified by sex are shown in Table 1. Mean age was 23.1 ± 1.52 years for females, and 23.1 ± 2.72 years for males and mean T1D duration was 14.79 ± 3.22 and 15.4 ± 2.96 years respectively, with 54 % of the female cohort using an insulin pump. Mean BMI was 26.11 ± 5.09 kg/m^2 with 53 % of the cohort being categorized as overweight or obese. Participants were predominantly white, non-smokers, did not consume alcohol, and did not have lifetime long-bone fractures. Mean HbA1c (%) at the time of study was 7.80 ± 1.52, and 7.1 ± 0.88 for females and males, respectively.

3.2. Physical activity characteristics

The PA characteristics of the cohort are shown in Table 2. On average, participants wore the accelerometer for 7.3 ± 0.73 days. Participants spent a mean of 138.6 ± 60.2 min of accelerometer recorded wear-time per day engaging in light PA, 33.3 ± 24.7 min of accelerometer recorded wear-time per day engaging in moderate PA, and 2.1 ±

Table 1
Demographic and clinical characteristics stratified by sex.

	Females	Males	Reference range (36)
	N = 13	N = 6	
Age at HR-pQCT, years	23.1 ± 1.52	23.1 ± 2.72	
Ethnicity			
White	7.0 (53.8)	3.0 (50.0)	
Other	6.0 (46.2)	3.0 (50.0)	
Height (cm)	164.6 (152.0–171.5)	179.9 (173.0–189.1)	Females:163.0–167.0 Males: 171.8–180.7
Weight (kg)	74.5 (60.0–101.2)	74.9 (64.6–108)	Females: 57.4–70.5 Males:70.4–85.4
Body Mass Index (kg/m^2)	27.6 (21.0–37.0)	23.0 (20.85–30.2)	Females: 21.0–25.2 Males: 22.7–26.9
Normal (18.5–24.9)	4.0 (30.8)	5.0 (83)	
Overweight (25.0–29.9)	4.0 (30.8)	0.0 (0)	
Obese (≥30)	5.0 (38.5)	1.0 (17)	
Diabetes characteristics			
Diabetes duration, years	14.8 ± 3.2	15.4 ± 3.0	
Insulin regimen			
Injection only	6 (46.2)	3 (50)	
Pump	7 (53.8)	3 (50)	
Hemoglobin A1c (%)	7.80 ± 1.52*	7.1 ± 0.88	
Smoking status			
Yes	1.0 (7.7)	0.0 (0.0)	
No	12.0 (92.3)	6.0 (100.0)	
Alcohol consumption			
Yes	3.0 (23.1)	2.0 (33.0)	
No	10.0 (76.9)	4.0 (67.0)	
Total number lifetime, long bone fractures			
0	10.0 (76.9)	4.0 (66.7)	
1	2.0 (15.4)	1.0 (16.7)	
2	1.0 (7.7)	1.0 (16.7)	
3	0.0 (0)	0.0 (0)	

Data are expressed as n (%) or mean ± SD. Height, weight and Body Mass Index are reported as mean (range). Reference ranges from Whittier et al. for the age range of 20–29 years (Whittier et al., 2020b)

* HbA1c missing for one participant.

Table 2
Physical activity characteristics of participants.

Physical activity parameter	Study population N = 19
Accelerometer wear time (mean number of days)	7.26 ± 0.73
Sedentary time	
Sedentary time (mean min/day)	821.61 ± 157.30
Sedentary time (% of accelerometer recorded wear-time activity/24 h)	57.06 ± 10.92
Active time	
Light intensity activity (mean min/day)	138.59 ± 60.18
Light intensity activity (% of accelerometer recorded wear-time activity/24 h)	9.62 ± 4.18
Moderate intensity activity (mean min/day)	33.32 ± 24.72
Moderate intensity activity (% of accelerometer recorded wear-time activity/24 h)	2.31 ± 1.72
Vigorous intensity activity (mean min/day)	2.06 ± 3.25
Vigorous intensity activity (% of accelerometer recorded wear-time activity/24 h)	0.14 ± 0.23
MVPA (mean min/day)	35.38 ± 26.47
MVPA (% of accelerometer recorded wear-time activity/24 h)	2.46 ± 1.84
Met the CSEP guidelines for MVPA, n (%)	12 (63 %)

Data are expressed as % or mean ± SD; MVPA = moderate to vigorous physical activity.

3.3 min of accelerometer recorded wear-time per day engaging in vigorous PA. With moderate and vigorous PA combined, participants completed an average of 35.4 ± 26.5 min of accelerometer recorded wear-time per day of MVPA. A total of 12/19 (63 %) of the participants met the Canadian Society for Exercise Physiology (CSEP) PA recommendations of accumulating ≥150 min per week of MVPA (Ross et al., 2020). However, on average, 57 % of recorded wear time activity per day was spent engaging in sedentary behaviours.

3.3. HR-pQCT Z-scores

For the tibia and radius, mean cortical *Z*-score measures and trabecular *Z*-scores are summarized in Table 3.

3.4. PA and bone microarchitecture associations

Associations between MVPA and HR-pQCT *Z*-score measures are presented in Table 4. At the tibia, MVPA was significantly associated (inverted U-shaped curve) with trabecular number ($\beta = -0.0008$, $p = 0.01$) with a threshold of 44 min. Furthermore, significant associations (U-shaped curve) were also found with trabecular spacing ($\beta = 0.0008$, $p = 0.02$) and inhomogeneity of trabecular network ($\beta = 0.0008$, $p = 0.01$). Thresholds were reached at 43 and 42 min of MVPA, respectively (Fig. 1). The same significant quadratic associations were seen between MVPA and HR-pQCT raw data measures (Supplementary Table 1). These significant quadratic associations were also observed when the single datapoint of a high MVPA (approx. 90 min/day) was excluded.

Associations between light PA and HR-pQCT *Z*-score measures are presented in Table 5. There were no significant associations between light PA and HR-pQCT outcome *Z*-scores ($p > 0.05$ for all).

Table 3
HR-pQCT parameter *Z*-scores of participants.

HR-pQCT variables	Tibia *Z*-scores N = 19	Radius *Z*-scores N = 19
Cortical		
CtAr [mm^2]	0.06 ± 1.4	0.06 ± 0.8
CtVBMD [HA/cm^3]	0.6 ± 1.4	1.3 ± 1.7
CtPo [%]	0.5 ± 1.2	0.08 ± 1.2
CtTh [mm]	−0.2 ± 1.6	0.2 ± 1.1
Trabecular		
TbAr [mm^2]	0.1 ± 1.4	0.4 ± 1.3
TbBMD [HA/cm3]	−1.0 ± 0.8	−0.8 ± 1.1
TbN [mm-1]	−0.9 ± 2.0	−0.5 ± 1.1
TbTh [mm]	−0.9 ± 1.0	−0.5 ± 1.2
TbSp [mm]	0.3 ± 1.0	0.5 ± 1.1
Tb1NSD [mm]	0.3 ± 1.4	0.5 ± 1.0
Failure load [N]	0.7 ± 0.90	0.2 ± 1.0

Data are expressed as mean ± SD.

4. Discussion

To our knowledge, this is the first cross-sectional study that has characterized the association between PA levels using accelerometry and HR-pQCT measures in a cohort of young adults with T1D. The main findings of the study were: 1) 63 % of participants met the CSEP PA guidelines for MVPA of at least 150 min per week (Ross et al., 2020); however, 2) participants spent most of their time in sedentary pursuits, and 3) significant associations were found between, MVPA and several HR-pQCT bone measures, mainly at the tibia.

4.1. Physical activity levels

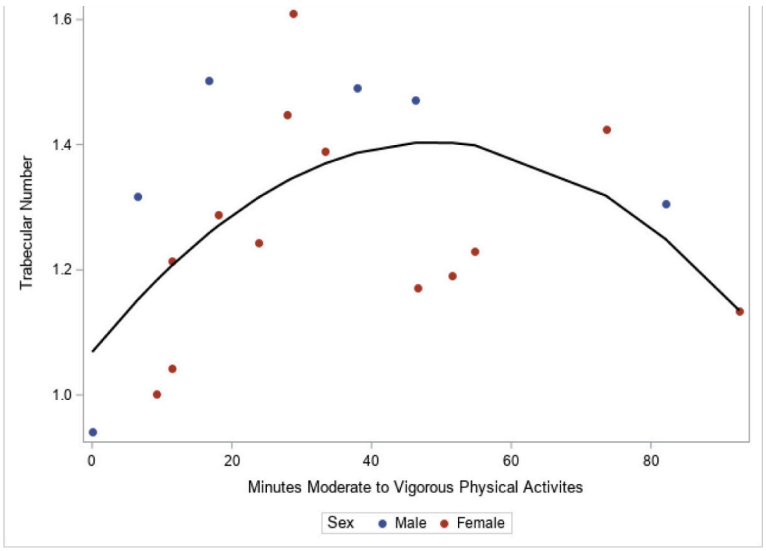
In the current study, over 60 % of young adults with T1D met or exceeded one component of the Canadian 24-h movement guidelines of obtaining at least 150 min of MVPA per week (Ross et al., 2020). This is in contrast with other studies in youth and adults T1D which report poorer uptake of MVPA (Keshawarz et al., 2018; Finn et al., 2022; Wu et al., 2021). For example, in one study that used a motion sensor (SenseWear Pro 3 Armband) to measure the PA in 75 Canadian adults

Table 4
Associations between mean daily minutes of MVPA and HR-pQCT *Z*-scores at the tibia and radius.

HR-pQCT variables	Tibia N = 19			Radius N = 19		
	β	*p*	R^2	β	*p*	R^2
Ct.Ar (mm^2)						
Linear	−0.0238	0.5054	0.0385	−0.0048	0.868	0.0121
Quadratic	0.0004	0.3534	0.0904	0.0001	0.7618	0.0179
Ct.BMD (mg HA/cm^3)						
Linear	0.0057	0.8844	0.084	0.0206	0.7199	0.0004
Quadratic	0	0.9652	0.0086	−0.0002	0.7248	0.0083
Ct. Po (%)						
Linear	0.033	0.4093	0.0346	−0.039	0.366	0.0248
Quadratic	−0.0003	0.5213	0.0599	0.0003	0.4451	0.0632
Ct.Th (mm)						
Linear	−0.0127	0.8205	0.0000	−0.0091	0.8077	0.0088
Quadratic	0.0001	0.8076	0.0039	0.0001	0.8857	0.0101
Tb.Ar (mm^2)						
Linear	−0.0034	0.9169	0.0769	0.0119	0.778	0.0517
Quadratic	0.0002	0.6542	0.0887	0.0000	0.9834	0.0517
Tb.BMD (mg HA/cm^3)						
Linear	0.0136	0.6164	0.0004	0.0289	0.4067	0.0004
Quadratic	−0.0002	0.5858	0.0193	−0.0003	0.3997	0.0451
Tb.N (1/mm)						
Linear	0.0772	**0.0108***	0.0347	0.0394	0.1802	0.0000
Quadratic	−0.0008	**0.0147***	0.3420	−0.0004	0.1619	0.1185
Tb.Th (mm)						
Linear	−0.0511	0.1459	0.0175	−0.007	0.8594	0.0141
Quadratic	0.0005	0.1731	0.1283	0.0001	0.7453	0.0208
Tb.Sp (mm)						
Linear	−0.0765	**0.0123***	0.0224	−0.0443	0.1631	0.0012
Quadratic	0.0008	**0.0150***	0.3322	0.0005	0.1363	0.1343
Tb.1NSD (mm)						
Linear	−0.0782	**0.0113***	0.0162	−0.049	0.0994	0.0079
Quadratic	0.0008	**0.0128***	0.3398	0.0006	0.0698	0.1973
Failure load						
Linear	−0.0259	0.3492	0.0549	0.0069	0.8327	0.0178
Quadratic	0.0004	0.2093	0.1462	0.0000	0.9501	0.0181

Significant associations have been bolded and noted with *.

a)



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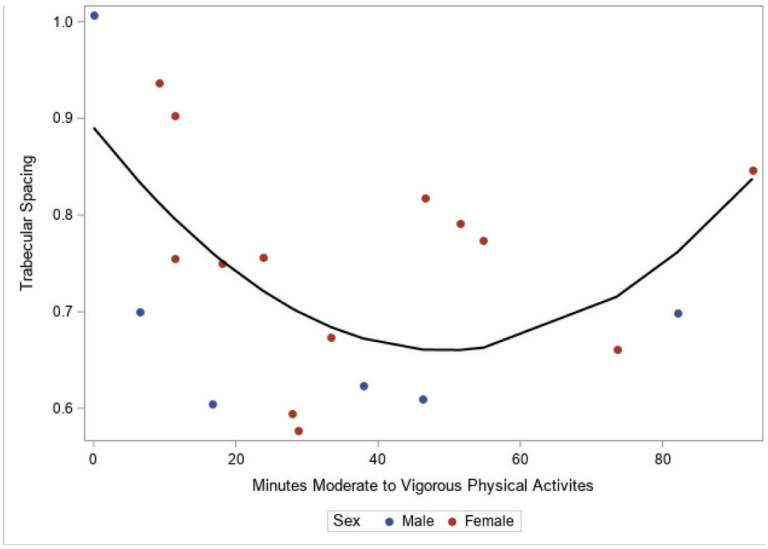

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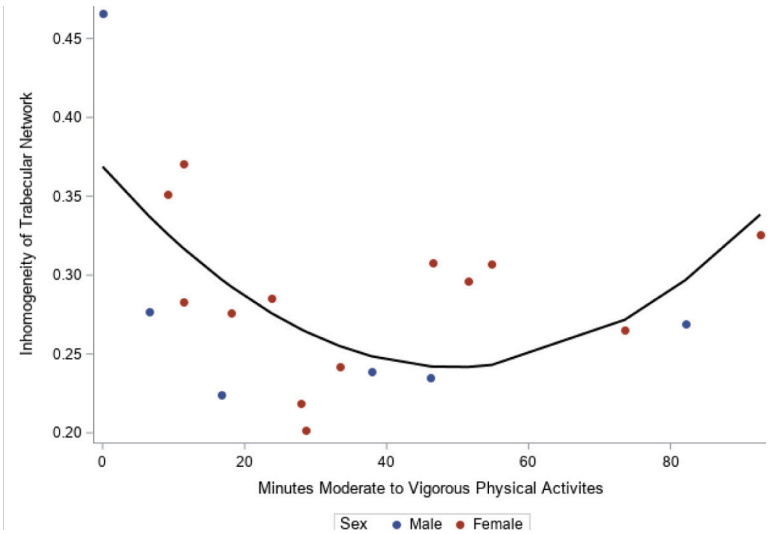

Fig. 1. a) Inverse U-shaped association between minutes of MVPA and trabecular number *Z*-score at the tibia; b) U-shaped association between minutes of MVPA and trabecular spacing *Z*-score at the tibia; c) U-shaped association between minutes of MVPA and inhomogeneity of trabecular network *Z*-score at the tibia.

Table 5
Associations between mean daily minutes of light physical activity and HR-pQCT *Z*-scores at the tibia and radius.

HRpQCT variables	Tibia N = 19		Radius N = 19	
	β	*p*	β	*p*
Ct.Ar (mm^2)				
Linear	−0.0111	0.4584	−0.0003	0.9789
Quadratic	0.0000	0.5059	0.0000	0.9534
Ct.BMD (mg HA/cm^3)				
Linear	0.0122	0.4412	0.0236	0.3053
Quadratic	0.0000	0.4757	−0.0001	0.2649
Ct. Po (%)				
Linear	0.0042	0.7995	−0.0088	0.6189
Quadratic	0.0000	0.7903	0.0000	0.6827
Ct.Th (mm)				
Linear	−0.0116	0.6086	−0.0043	0.7741
Quadratic	0.0000	0.7441	0.0000	0.9941
Tb.Ar (mm^2)				
Linear	0.0045	0.7396	0.0115	0.4894
Quadratic	0.0000	0.9585	0.0000	0.7804
Tb.BMD (mg HA/cm^3)				
Linear	0.0013	0.9065	0.0035	0.8098
Quadratic	0.0000	0.7448	0.0000	0.7802
Tb.N (1/mm)				
Linear	0.0225	0.0827	0.0078	0.5280
Quadratic	−0.0001	0.1218	0.0000	0.5393
Tb.Th (mm)				
Linear	−0.0230	0.0918	−0.0154	0.3388
Quadratic	0.0001	0.1961	0.0001	0.3300
Tb.Sp (mm)				
Linear	−0.0233	0.0738	−0.0107	0.4223
Quadratic	0.0001	0.1006	0.0000	0.4133
Tb.1NSD (mm)				
Linear	−0.0250	0.0561	−0.0144	0.2560
Quadratic	0.0001	0.0849	0.0001	0.2566
Failure load				
Linear	−0.0060	0.6132	0.0069	0.6093
Quadratic	0.0000	0.7049	0.0000	0.6203

with T1D and 75 without, only 43 % of women and 55 % of T1D men were classified as being active (Brazeau et al., 2012). In a recent study of children and adolescents (mean age ~ 12 years) with T1D recruited from the Saskatchewan Health Authority Pediatric Diabetes clinic, Diabetes Camp (summer camp for children with T1D), and related diabetes events from 2018 to 2023, it was found that children and adolescents with T1D engaged in less PA than typically developing peers when measured using the Physical Activity Questionnaire for Children (Zheng et al., 2024). Interestingly, when MVPA and VPA were determine by accelerometry, there were no differences in PA between children with T1D and typically developing peers, and children with T1D engaged in a mean of 45 ± 23 MVPA min/day (Zheng et al., 2024). This is somewhat similar to our current findings, which reported that on average young adults with T1D participated in 35 ± 27 min of MVPA/day (Zheng et al., 2024). It could be that participants in both Zheng et al. (2024) and the current study had relatively good metabolic control (HbA1c) suggesting an ongoing commitment to their diabetes management, including adherence to PA recommendations. Nonetheless, although many of our current participants met CSEP MVPA guidelines, our group was overall highly sedentary. More specifically, the mean sedentary time of our participants was over 13 h/day, which far exceeds the suggested maximum 8 h/day by the Canadian 24-h movement guidelines (Ross et al., 2020). Sedentary behaviour has been defined as engaging in activity with a low energy expenditure, specifically ≤1.5 metabolic equivalents (METs) and includes activities such as sitting or lying down (Tremblay et al., 2017; Mansoubi et al., 2015). The high amount of sedentary time in individuals with T1D in the current study is consistent with other published research (Huerta-Uribe et al., 2023), including one study in 215 children with T1D who were found to be significantly more sedentary (via accelerometry) compared to healthy controls (Czenczek-Lewandowska et al., 2019). Sedentary behaviour is important because research demonstrates that it is independently associated with negative health-related outcomes, including mortality, in the general population (Patterson et al., 2018; Park et al., 2020).

4.2. Significant associations: MVPA and bone

In this study, MVPA was found to have significant quadratic associations with trabecular number, spacing, and inhomogeneity of trabecular network at the distal tibia, but not at the radius. The distal tibia is a weight bearing bone and the underlying biology links loads to remodeling, compared with the distal radius, which is a non-load bearing site (Langsetmo et al., 2020). We also found that the duration of MVPA was associated with some trabecular parameters at the distal tibia, but not with any cortical bone components; findings which are partially consistent with what is reported in the literature. For example, the University of British Columbia Healthy Bones Study (HBSII), which spans the adolescent growth spurt and used HR-pQCT to assess bone outcomes, found that adolescents who participated in longer periods of MVPA had greater trabecular bone tissue volume at both the radius and tibia (Gabel et al., 2017). Similar associations were observed between impact loading PA and trabecular bone density and trabecular number at the distal tibia in adolescent females (McKay et al., 2011). In another study, 91 female US army recruits that completed a physically demanding program (basic combat training), and the distal tibia metaphysis, primarily trabecular bone outcomes (trabecular thickness, trabecular number, and total and trabecular volumetric bone density measured by HR-pQCT) increased significantly by 1–2 % over the training period. In Zheng et al. children with T1D had lower trabecular density, bone volume fraction, thickness and number at both the distal radius and tibia, and higher trabecular separation at the distal radius compared to healthy peers (Zheng et al., 2024). PA (as determined by accelerometery) was not associated with bone outcomes in this study, however, PA as measured by survey mediated the between-group difference in trabecular number (Zheng et al., 2024).

However, there are reports to suggest that MVPA may impact cortical bone outcomes at the tibia as well. In the above study involving female army recruits, at the distal tibia metaphysis, cortical thickness increased significantly over the training period, while in contrast, both cortical tissue mineral density and cortical volumetric bone mineral density decreased significantly by 0.7 % (Hughes et al., 2018). In a study by Nissen et al. of female adult twin pairs, higher levels of PA (determined by self-completed questionnaire) were associated with cortical outcomes such as a larger cortical area and cortical BMD at the tibia (Nissen et al., 2023). In Zheng et al.'s study, children with T1D had higher cortical bone outcomes at the distal radius and higher cortical density and muscle density at both shaft sites compared to healthy peers, however, cortical bone parameters were not associated with PA (measured either by survey or accelerometry) (Zheng et al., 2024). These study results, combined with our lack of associations between PA and cortical bone outcomes in young adults with T1D, highlight the relative complexity of the PA and cortical bone health relationship. Indeed, our results suggest that the impact of MVPA on bone microarchitecture in the setting of T1D in young adults may be site (tibia) and bone compartment (trabecular) specific. This site specificity was also reported in a Canadian study of young adolescents (without T1D) where MVPA predicted variance in bone strength at the tibia, but not the radius (as measured by pQCT) (Kehrig et al., 2019). In addition, our data complements previous findings of a dose-response relationship between the quantity of load bearing PA and bone (Smith and Gilligan, 1996). Importantly, our observed PA-bone relationships are characterized by a U-shaped or inverted U-shaped curves, where more PA impacts certain bone outcomes up to a certain maximum amount of PA, after which there is a change in impact. This is somewhat in contrast to data which suggests that the bone response to a load may be linear in post-menopausal women (i.e., higher volumes of physical activity leads to

more impact on bone) (Gonzalo-Encabo et al., 2019), and in a pQCT study of young adolescents (Kehrig et al., 2019). Therefore, our findings suggest that the bone-PA relationship in young adults with T1D is complex, and that a simple linear dose-response relationship may not best describe how bone responds to PA in this group. Further investigations to confirm these findings are needed, as there may be a maximum PA quantity to target for optimum bone health in young adults with T1D.

4.3. Study strengths and limitations

Our study has some strengths and limitations to be noted. Strengths included the use of current optimal methodologies for measurement of bone (HR-pQCT) and daily physical activity (triaxial accelerometery) in a well characterized cohort of young adults with T1D. Our study adds unique data to the T1D literature regarding the impact of PA on bone health in young adulthood, where there has been limited research.

There are also some important limitations of this pilot study. Our small sample size did not allow for an evaluation of potential confounders nor for an examination of any potential interaction effects between light PA, MVPA and sedentary time, as well as any associations between diabetes parameters such as HbA1c, diabetes duration and HR-pQCT outcomes. We were not able to control for weight and BMI as potential confounders, although the weight and BMI we observed were similar to that reported in the database for a healthy population of 20–30 year olds (Whittier et al., 2020b), mitigating to some extent the need for adjustments for weight and BMI. As well, due to the sample being a convenience sample from a larger study, the results cannot be generalized to the general T1D population. We acknowledge that triaxial accelerometery is not without error, as the device is worn on the waist, and therefore may not detect differences between sitting and standing yielding an overestimated sedentary time. Although raw accelerometer counts (i.e., impact counts) have been linked to improved bone strength (Nissen et al., 2023), we did not calculate impact counts or impact count threshold. As well, it is important to acknowledge that quadratic findings may be impacted by datapoints at extremes (such as very high MVPA). Additionally, since accelerometers monitor accelerations within the center of body mass, which is key when recording weight-bearing activities and loading stimulus for lower extremity, our observed lack of association between bone outcomes at the radius and MVPA may be explained by this limitation. Further limitations include using a cross-sectional design, which means that causal changes to bone size, density, and microarchitecture resulting from PA over time cannot be inferred.

5. Conclusions

In this study of a small group of young adults with T1D, we found that while the MVPA component of the Canadian 24-h movement guidelines (150 min/week) (Ross et al., 2020) were met by many participants, the cohort was highly sedentary. Significant and non-linear associations were found between MVPA and bone microarchitecture that was site specific (tibia), and compartment specific (trabecular). These non-linear associations are interesting and novel, but larger studies are needed to further characterize the relationship between bone microarchitecture and PA in T1D. Confirmation of these findings may help with the adaption or development of exercise recommendations for young adults with T1D, especially with respect to optimizing bone health as an important outcome.

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CRediT authorship contribution statement

Sarah L. West: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Michelle Furman:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rahim Moineddin:** Formal analysis. **Etienne Sochett:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors (Sarah L West, Michelle Furman, Rahim Moineddin, and Etienne Sochett) have no conflicts of interest, or competing interest to declare.

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Data availability

Data will be made available on request.

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