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Suboptimal bone status for adolescents with low motor competence and developmental coordination disorder—It's sex specific

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ABSTRACT

Background: Australian adolescents with low motor competence (LMC) have higher fracture rates and poorer bone health compared to European normative data, but currently no normative data exists for Australians.

Aims: To examine whether there were bone health differences in Australian adolescents with LMC or Developmental Coordination Disorder (DCD) when compared to typically developing age-matched Australian adolescents.

Methods and Procedures: Australian adolescents aged 12–18 years with LMC/DCD (n = 39; male = 27; female = 12) and an Australian comparison sample (n = 188; boys = 101; girls = 87) undertook radial and tibial peripheral Quantitative Computed Tomography (pQCT) scans. Stress Strain Index (SSI (mm³)), Total Bone Area (TBA (mm²)), Muscle Density (MuD [mgcm³]), Muscle Area (MuA [cm²]), Subcutaneous Fat Area (ScFA [cm²]), Cortical Density (CoD [mgcm³]), Cortical Area (CoA [mm²]), cortical concentric ring volumetric densities, Functional Muscle Bone Unit Index (FMBU: (SSI/bone length)) and Robustness Index (SSI/bone length³), group and sex differences were examined.

Outcome and Results: The main finding was a significant sex-x-group interaction for Tibial FMBU (p = .021), Radial MuD (p = .036), and radial ScFA (p = .002). Boys with LMC/DCD had lower tibial FMBU scores, radial MuD and higher ScFA than the typically developing age-matched sample.

Conclusion and Implications: Comparisons of bone measures with Australian comparative data are similar to European findings however sex differences were found in the present study. Australian adolescent boys with LMC/DCD had less robust bones compared to their well-coordinated Australian peers, whereas there were no differences between groups for girls. These differences

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may be due to lower levels of habitual weight-bearing physical activity, which may be more distinct in adolescent boys with LMC/DCD compared to girls.

What this paper adds?

Little is known about the bone health of adolescents with LMC/DCD. Previously the authors have shown that bone health deficits are present when compared to European normative data. This study further explored these bone health differences in the Australian context, comparing Australian adolescents with LMC/DCD to typically developing age-matched Australian adolescents. The results revealed Australian adolescent boys with LMC/DCD had less robust bones compared to non-affected Australian peers, whereas there were no differences between groups for girls.

1. Introduction

Low motor competence (LMC) and a negative impact on activities of daily living are key features of Developmental Coordination Disorder (DCD) as described by DSM-V criteria (American Psychiatric Association, 2013). Australian adolescents with LMC, including participants with DCD, have fracture rates (26.9%) higher than their non-affected peers (4.6%) and have lower bone mineral density (BMD), particularly in their forearms, compared to European normative data (Hands et al., 2015). The aetiology of this bone deficit in adolescents with LMC/DCD is yet to be explored, however understanding the reasons for poorer bone health in this group is important for identifying strategies to reduce the risk of osteoporosis later in life (Julián-Almárcegui et al., 2015). The bone deficit observed is most likely indirectly related to a motor learning process. Specifically, children and adolescents with DCD have difficulties with the acquisition and execution of basic movement skills such as running, jumping, hopping and throwing and also have a higher incidence of falls (Dishman, Sallis, & Orenstein, 1985). This is a critically important modifiable characteristic, with these basic weight bearing movement skills well recognised for their role in developing bone mass and mineral density through interactions between muscle and bone throughout the developmental years of childhood to adolescence (Fuchs, Bauer, & Snow, 2001; Hart et al., 2017; Ireland, Sayers, Deere, Emond, & Tobias, 2016). For example, LMC in 1.5 year old infants was associated with poorer bone strength at 17 years in The Avon Longitudinal Study of Parents and Children (ALSPAC) (Ireland et al., 2016).

Children and adolescents with DCD exhibit lower physical activity levels, lower physical fitness (Cantell, Crawford, & Doyle-Baker, 2008; Hands & Larkin, 2006) and poorer metabolic indices (adiposity, resting heart rate, blood lipids and energy expenditure) compared to their typically developing peers (Cantell et al., 2008). A recent systematic review found that children with DCD chose not to participate in physically active play, recreational activities or other skill-based activities, and were subsequently less engaged in team sports than their peers (Zwicker, Harris, & Klassen, 2013). Many parents of children with DCD noted they were not able to keep up with their peers in active play and games (Missiuna, Moll, King, King, & Law, 2007).

This observed lower level of physical activity is likely related to poorer bone health in individuals with DCD as bone strength is strongly influenced by the mechanical loads imparted by gravitational and muscle loading (Hart et al., 2017; Schoenau & Fricke, 2008). Even in typically developing 8–13 year old girls, Farr (2011) found that reduced levels of physical activity duration, frequency and magnitude, were associated with poorer bone geometry and strength. This evidence is particularly concerning for individuals with DCD as approximately 40 percent of total bone mass is accumulated during adolescence alone, with up to 90% of bone mass accumulated by 20 years of age (Bianchi et al., 2010). Peak bone mass is a determinant of risk for osteoporosis in adulthood (Baroncelli, Bertelloni, Sadini, & Saggese, 2005; Weaver et al., 2016), hence improving peak bone mass during adolescence is important, and should be the focus of prevention programs in at-risk individuals (Baroncelli et al., 2005; Bianchi et al., 2010).

There are very few studies examining bone health in this potentially at risk group of adolescents with LMC/DCD, and little is known about the comparative bone strength of adolescents with compromised motor competence in Australia. Currently peripheral Quantitative Computed Tomography (pQCT) comparisons are based on European norms as no normative data exist for Australians. It has been suggested that the exercise-bone health correlation may vary by gender and ethnicity e.g. South African white and black children (Stagi, Cavalli, Cavalli, de Martino, & Brandi, 2016), yet we do not know if this applies between Australian or European cohorts, particularly in light of differences in climate and lifestyle. Further, sex adjusted normative data do not provide the flexibility to examine specific sex and age differences, as well as sex interactions to a typically developing cohort. Therefore the aim of the current study was to examine whether bone health differs between Australian adolescents with LMC (including a subset of adolescents with DCD) when compared to typically developing Australian sex and age-matched adolescents.

2. Materials and methods

This study conducted a re-analysis of a published dataset from AMPitup (Hands et al., 2015) (described below) which used previously standardised bone data to the reference database (Moyer-Mileur, Quick, & Murray, 2008; Neu, Manz, Rauch, Merkel, & Schoenau, 2001) and included any new participants enrolled during 2015–2017. This study examines the raw bone data prior to standardization (as per 2.4 below). The typically developing cohort was drawn from data from the Griffith University Bone Densitometry Research Laboratory (Weeks & Beck, 2012a; Nogueira, Weeks, & Beck, 2014; Nogueira, Weeks, & Beck, 2015; Rantalainen, Weeks, Nogueira, & Beck, 2015; Rantalainen, Weeks, Nogueira, & Beck, 2016; Weeks & Beck, 2012b; Weeks, Hirsch, Moran, & Beck,

2011) matched to the AMPitup cohort for this study. Human Research Ethics Committee (HREC) approval was granted (AMPitup: The University of Notre Dame Australia HREC Reference 011004F, 09004F, 09050F, 09039F; and Griffiths University HREC Reference PES/25/11/HREC; PES/12/05/HREC, PES/09/09/HREC), with informed consent provided.

2.1. Adolescents with LMC/DCD

The Adolescent Movement Program (AMPitup) is an ongoing exercise clinic designed for adolescents with movement difficulties based at The University of Notre Dame Australia. For this study, AMPitup participants ($n = 39$; male = 27; female = 12) were aged between 12 and 18 years (Hands et al., 2015). Participant's motor performance was screened using the McCarron Assessment of Neuromuscular Development (MAND) (McCarron, 1997). This 10-item test consists of five fine and five gross motor tasks and the scaled scores for the 10 tasks are summed and converted to a Neuromuscular Developmental Index (NDI). The MAND has established validity and reliability with this age group (McCarron, 1997), is an accurate discriminator of motor impairment (Tan, Parker, & Larkin, 2018) and is considered a useful test of motor performance for Australian children and adolescents (Hands, Larkin, & Rose, 2013). Participants were eligible for the program if they had a formal DCD diagnosis. Other participants were included if they had a NDI of 85 or below (≤ 1 SD) (mild motor disability DSM-V Criterion A, American Psychiatric Association, 2013) or a parent reported history of movement difficulties (such as poor coordination or clumsiness, slowness and inaccuracy of motor skills DSM-V Criterion C, American Psychiatric Association, 2013). The negative impact on daily living, school, leisure and play activities (DSM-V Criterion B, American Psychiatric Association, 2013) was discussed during the selection screening, but was not formally assessed. Those with significant intellectual, neurological or physical disabilities (as reported by parents/caregivers/referring practitioner) were excluded (DSM-V Criterion D, American Psychiatric Association, 2013). Participants were invited to participate in the bone health aspect of the AMPitup program upon acceptance to the program. Most participants received bone scans prior to the commencement of the exercise intervention. For a few participants, the initial bone scan was taken whilst they were enrolled in the twice weekly exercise program. De-identification of data prior to this study data analysis did not permit any differentiation between participants with LMC/DCD.

2.2. Healthy Australian age-matched adolescents

The comparison group of typically developing age-matched Australian adolescents ($n = 188$; male = 101; female = 87) were drawn from data collected at the Bone Densitometry Research Laboratory at Griffith University (QLD, Australia) (Griffith dataset) (Nogueira et al., 2014, 2015; Rantalainen et al., 2015; Rantalainen et al., 2016; Weeks et al., 2011; Weeks & Beck, 2012b; Weeks & Beck, 2012a). Images were extracted for individuals aged between 12 and 18 years-of-age to match with the AMPitup dataset.

2.3. Anthropometry

For the AMPitup data, height was measured using a stadiometer (Mentone Educational Centre; Victoria, Australia), with the average recorded to the nearest 0.1 cm; and weight was measured to the nearest 0.1 kg using a digital weight scale (HoMEDICS; Victoria, Australia). For the Griffiths data, height (stretch-stature method) was measured to the nearest millimetre using a portable stadiometer (HART Sport and Leisure, Brisbane, Queensland, Australia); and weight was measured to the nearest 0.1 kg using a portable digital scale (Soehnle, Hamburg, Germany). Tibial length was measured from the tibial plateau (proximal) to the medial malleolus (distal); and forearm length was measured from lateral epicondyle (proximal)(AMPitup)/tip of the olecranon (proximal) (Griffiths) to the ulnar styloid process (distal); each also performed in triplicate with the average recorded to the nearest 0.1 cm and retained for use during subsequent in-vivo skeletal assessments.

2.4. Bone assessments

Peripheral Quantitative Computed Tomography (pQCT, XCT-3000, Stratec® Medizintechnik GmbH, Pforzheim, Germany) was used to evaluate cross-sections of the tibia and radius at 66% from the distal endplates (defined from a scout view) of the tibia (talocrural joint) and radius (radioulnar joint) respectively (slice thickness 2.3 mm, AMPitup: pixel size 0.4×0.4 mm, Griffith: pixel size 0.5×0.5 mm), calibrated according to manufacturer specifications. pQCT provides an assessment of volumetric bone mineral density, macroscopic material, geometrical structure, biomechanical parameters and stress strain index to describe bone strength (Stagi et al., 2016). Participants were seated in a stationary chair, adjusted to their height, with their limb centrally positioned in the gantry, and secured to a limb holder. pQCT scans were taken of the non-dominant limb. All AMPitup participant scans were conducted at Princess Margaret Hospital for Children in the Department of Medical Imaging, Perth, Western Australia. All Griffith participant scans were conducted at the Bone Densitometry Research Laboratory at Griffith University, Gold Coast, Queensland.

2.5. Bone analysis

Bone scans were visualised and manually categorised according to visible motion artefact and divided into acceptable or unacceptable for all data (Rantalainen et al., 2017). For the LMC/DCD group, 39 tibial and 26 radial scans were available for further analysis. For the Griffith comparison group, 175 tibial and 114 radial scans were available for further analysis.

Stress Strain Index (SSI [mm^3]), Total Bone Area (TBA [mm^2]), Muscle Density (MuD [mgcm^3]), Muscle Area (MuA [cm^2]), Subcutaneous Fat Area (ScFA [cm^2]), Cortical Density (CoD [mgcm^3]), Cortical Area (CoA [mm^2]), Endo-cortical [mgcm^3]), Mid-

cortical [mgcm^3), and Peri-cortical [mgcm^3] concentric ring volumetric densities were calculated with BoneJ ImageJ-plugin (rsbweb.nih.gov/ij) (Doubé et al., 2010; Rantalainen, Nikander, Heinonen, Daly, & Sievanen, 2011). Functional muscle bone unit Index (FMBU: SSI/bone length) and Robustness Index (SSI/bone length³) were subsequently computed (Rantalainen et al., 2016).

2.6. Data analysis

Statistical analysis was conducted using IBM SPSS v24 (IBM Corp Released, 2016). Bone measures were not normally distributed (Shapiro-Wilk $p < .05$) hence specific group differences were examined using Mann-Whitney U Test, except for Tibial CoD and Tibial concentric ring volumetric densities with group differences assessed using an Independent T-test. A General Linear Model (GLM) for each bone measure was used to determine differences between groups, controlling for sex, age and bone length (as a surrogate for growth and hormone differences), whilst investigating possible interactions between groups with sex and age. Model residuals were inspected and did not violate the assumptions of the GLM. Statistical significance was set at $p < .05$.

3. Results

Participants with LMC/DCD were on average one year younger (14.4 ± 1.3 years) than the comparison group (15.3 ± 1.8 years) ($p = .007$), although this was not statistically significant when analysed according to sex (boys: $p = .102$; girls: $p = .096$), with both equally represented for the radius (54.1% male, 43.9% female) and tibia measures (53.2% male, 46.8% female). There were no significant differences between the LMC/DCD group and comparison group for tibial bone length ($p = .446$) and forearm bone length ($p = .638$), nor when investigated separately for boys ($p = .392$, $p = .276$) and girls ($p = .201$, $p = .909$) respectively.

Sex differences were observed for the tibia with the boys' median scores higher than girls' for FMBU Index (boys median = 41.7 girls median = 37.8 $p = .023$, Fig. 1), total bone area (boys median = 597.9mm^2 girls median = 552.5mm^2 $p < .001$), SSI (boys median = 2323 girls median = 2097 $p < .001$), and MuA (boys median = 58.1cm^2 girls median = 54.4cm^2 $p = .020$), but lower for ScFA (boys median = 12.8cm^2 girls median = 21.7cm^2 $p < .001$), and CoA (boys median = 399mm^2 girls median = 348mm^2 $p < .001$), CoD ($t = -3.17$ $p = .002$), Mid-cortical ($t = -4.96$ $p < .001$) and Peri-cortical ($t = -5.86$ $p < .001$) concentric ring volumetric densities (Table 1). For the radius, boys median scores were lower than girls for FMBU Index (boys median = 9.1 girls median = 10.4 $p < .001$), ScFA (boys median = 2.9cm^2 girls median = 9.1cm^2 $p < .001$, Fig. 3b), Mid-cortical (boys median = 1091mgcm^2 girls median = 1156mgcm^2 $p = .002$) and Peri-cortical (boys median = 931mgcm^2 girls median = 985mgcm^2 $p = .002$) concentric ring volumetric densities, but higher than girls for MuA (boys median = 29.7cm^2 girls median = 23.2cm^2 $p < .001$) and CoA (boys median = 102.8mm^2 girls median = 94.8mm^2 $p = .028$) (Fig. 2).

Participants with LMC/DCD had lower tibial scores than the comparison group for robustness index (LMC/DCD median = 37.1 comparison median = 39.2 $p = .008$), MuD (LMC/DCD median = 79.0mgcm^3 Comparison median = 79.5mgcm^3 $p = .005$, Fig. 3c), ScFA (LMC/DCD median = 24.7cm^2 Comparison median = 14.6cm^2 $p < .001$), CoA (LMC/DCD median = 343mm^2 Comparison median = 385mm^2 $p = .005$), and Peri-cortical concentric ring volumetric densities ($t = 2.34$ $p = .020$) (Table 1). Participants with LMC/DCD also reported lower radius FMBU Index (LMC/DCD median = 9.0 comparison median = 9.7 $p = .046$), robustness index (LMC/DCD median = 11.9 comparison median = 14.5 $p = .009$) but higher ScFA (Comparison median = 5.0cm^2 DCD median = 11.1cm^2 $p < .001$). There were no other group differences. Descriptions of all bone parameters separated for boys and girls, LMC/DCD and typically developing are provided in Table 1 for the tibia and Table 2 for the radius.

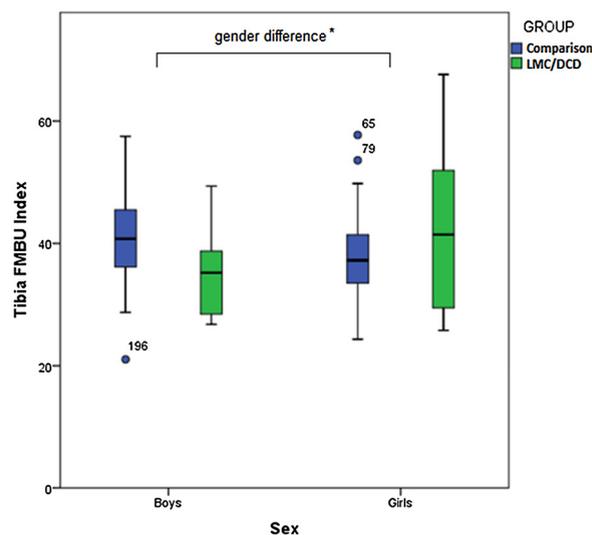


Fig. 1. Box plot of group differences according to sex for Functional Muscle Bone Unit (FMBU) Index at the 66% site of the tibia. * $p < .05$. LMC/DCD = Low Motor Competence / Developmental Coordination Disorder.

Table 1
Description of bone parameters and GLM post-hoc group comparisons of the 66% cross-section for the Tibia.

Bone Parameter	Comparison Group		LMC/DCD Group		GLM Pairwise comparison		
	Boys Mean (SD)	Girls Mean (SD)	Boys Mean (SD)	Girls Mean (SD)	Sex	Group	Sex x Group
<i>Bone Length (mm)</i>	381.8 (44.2)	373.5 (26.1)	392.9 (44.2)	394.0 (35.7)			
FMBU Index	41.7 (6.5)	38.1 (6.3)	36.7 (8.0)	40.4 (13.6)	p = .283	p = .214	*p = .021
Total Area (mm ²)	644.1 (129.7)	556.0 (97.5)	593.9 (126.4)	373.8 (133.7)	p = .126	p = .440	p = .234
SSI (mm ³)	2553.5 (749.8)	2133.4 (492.3)	2225.5 (640.2)	1949.5 (401.6)	*p = .011	*p = .030	p = .860
Robustness Index	41.8 (11.1)	41.1 (7.5)	37.2 (9.2)	35.1 (8.4)	*p = .012	p = .078	p = .529
Muscle Density (mgcm ³)	79.8 (1.5)	79.5 (1.3)	79.2 (2.1)	78.4 (1.3)	p = .073	*p = .009	p = .509
Muscle Area (cm ²)	61.5 (16.3)	56.3 (10.5)	60.8 (14.8)	52.5 (12.5)	*p = .005	p = .796	p = .213
Subcutaneous Fat Area (cm ²)	13.8 (8.7)	20.8 (7.9)	27.4 (12.1)	27.9 (10.9)	*p = .009	*p < .001	p = .103
Cortical Density (mgcm ³)	858.9 (55.1)	894.9 (53.6)	878.1 (59.7)	872.7 (77.3)	p = .921	p = .155	p = .118
Cortical Area (mm ²)	418.9 (80.8)	363.8 (57.8)	370.6 (86.2)	333.9 (41.0)	*p = .001	*p = .001	p = .877
Volumetric densities							
Endo-cortical (mgcm ³)	822.3 (86.82)	858.3 (89.6)	861.3 (94.9)	853.3 (89.6)	p = .560	p = 0.63	p = .486
Mid-cortical (mgcm ³)	1056.4 (53.2)	1104.8 (54.0)	1068.9 (53.2)	1077.0 (68.5)	p = .133	p = .353	p = .112
Peri-cortical (mgcm ³)	1007.0 (58.5)	1063.3 (57.0)	1001.3 (53.0)	1020.8 (74.3)	*p = .006	p = .458	p = .192

Note. Pairwise comparisons are based on the estimated marginal means from the General Linear Model (GLM), controlling for age and bone length, and adjusting for multiple comparisons using Bonferroni correction. ***Bolded p < .05.**

LMC/DCD = Low Motor Competence / Developmental Coordination Disorder SD = standard deviation FMBU = Functional Muscle Bone Unit SSI = Stress Strain Index.

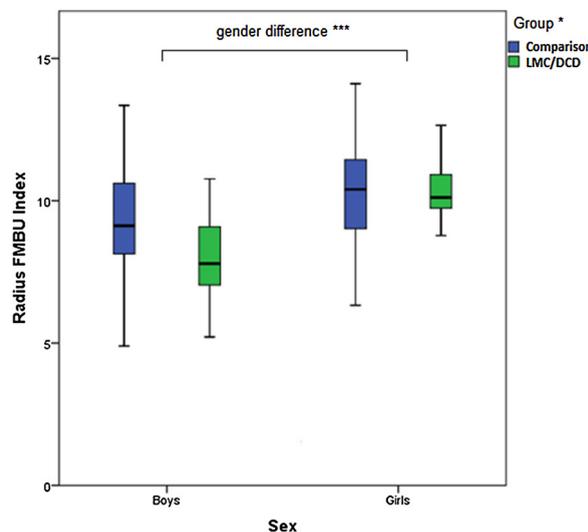
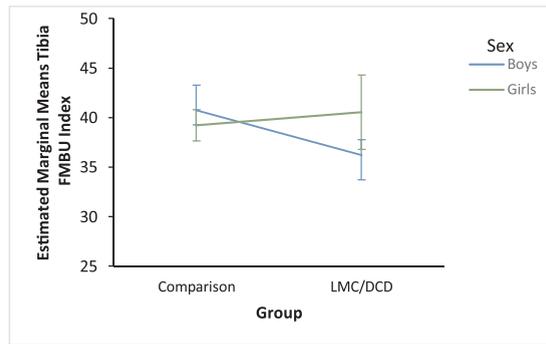


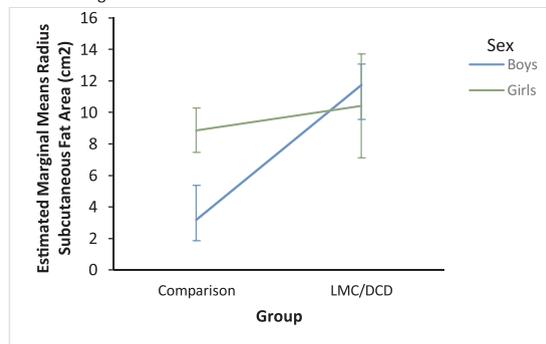
Fig. 2. Box plot of group differences according to sex for Functional Muscle Bone Unit (FMBU) Index at the 66% radius site. * p < .05 ***p < .001. LMC/DCD = Low Motor Competence / Developmental Coordination Disorder.

The GLM further explored group differences while controlling for the influence of age and bone length. GLM Bonferroni adjusted pairwise comparisons (Tables 1 and 2) reported sex only differences for tibial robustness index (p = .012) and tibial MuA (p = .005) with boys higher; tibial Peri-cortical volumetric density (p = .006), and FMBU Index of the radius (p < .001) with boys lower than girls. Group only differences were reported for tibial MuD (p = .009), radial SSI (p = .040) with the LMC/DCD group scoring lower. Both sex and group differences were observed for tibial SSI (p = .011 and p = .030 respectively), ScFA (p = .009 and p < .001 respectively), CoA (p = .001 for both) and radial mid-cortical volumetric density (p = .032 and p = .010 respectively). Boys had higher overall tibial SSIs, tibial CoA, lower tibial ScFA and radial mid cortical volumetric densities than girls. Adolescents with LMC/DCD had lower tibial SSIs, tibial CoA and higher tibial ScFA and radial mid cortical volumetric densities than their age-matched comparison group.

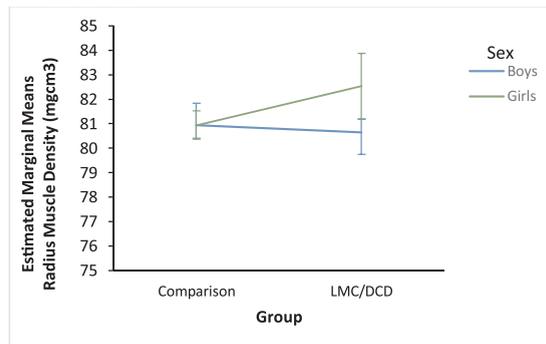
Fig. 3 depicts the GLM estimated marginal means plots for the three significant sex x group interaction models which adjusts for age and bone length. Here, intersecting lines demonstrate that the difference in bone scores between boys and girls is different between the LMC/DCD group and comparison group, and in most cases this difference is pronounced for boys. GLM for FMBU Index of the tibia found bone length (p < .001) and a sex x group interaction (p = .021) were significant contributors. In contrast, the healthy age-matched adolescent boys (i.e. the comparison group) had a tibial FMBU Index six units higher (p = .021) than the other



A. GLM Estimated Marginal Means for Tibia FMBU Index. Covariates appearing in the model are evaluated at the following values: age=15.09 years, tibia bone length = 384.79mm.



B. GLM Estimated Marginal Means for Radius Subcutaneous Fat Area (cm²). Covariates appearing in the model are evaluated at the following values: age=14.91 years, forearm bone length =263.22 mm.



C. GLM Estimated Marginal Means for Radius Muscle Density (mgcm³). Covariates appearing in the model are evaluated at the following values: age=14.91 years, forearm bone length = 263.22mm .

Fig. 3. General Linear Model (GLM) Estimated Marginal Means plots adjusted for covariates age (years) and bone length (mm) for (A) Tibia Functional Muscle Bone Unit (FMBU) Index, (B) Radius Subcutaneous Fat Area (cm²) and (C) Radius Muscle Density (mgcm³). Each model had a significant sex x group interaction ($p < .05$). LMC/DCD = Low Motor Competence / Developmental Coordination Disorder.

group combinations (Fig. 3a). GLM for the radius ScFA reported a group ($p < .001$) and a sex x group interaction ($p = .002$) were significant contributors. The healthy age-matched adolescent boys (i.e. the comparison group) had a ScFA seven units lower ($p = .002$) than the other group combinations (Fig. 3b). The GLM for radius MuD found gender ($p = .021$) and a sex x group interaction ($p = .036$) were significant contributors. The healthy age-matched adolescent boys (i.e. the comparison group) had a radial MuD two units higher ($p = .036$) than the other group combinations (Fig. 3c). Although other GLM did not report significant sex x group interactions, estimated marginal means plots depicted similar trends for tibia bone measures CoD, endo-, mid- and peri-cortical volumetric densities; and radius bone measures CoD, CoA, endo- and peri-cortical volumetric densities.

Table 2

Description of bone parameters and GLM post-hoc group comparisons of the 66% cross-section for the Radius.

Bone Parameter	Comparison Group		LMC/DCD Group		GLM Pairwise comparison		
	Boys Mean (SD)	Girls Mean (SD)	Boys Mean (SD)	Girls Mean (SD)	Sex	Group	Sex x Group
<i>Forearm Length (mm)</i>	262.6 (27.9)	253.3 (16.4)	264.4 (18.4)	254.5 (21.4)			
Radius FMBU Index	9.3 (1.6)	10.5 (1.4)	8.3 (1.4)	10.6 (1.4)	*p < .001	p = .300	p = .226
Radius Total Area (mm ²)	143.5 (28.7)	129.5 (23.6)	125.3 (20.6)	120.3 (12.6)	p = .953	p = .053	p = .339
Radius SSI (mm ³)	288.1 (91.2)	251.7 (61.9)	233.8 (44.7)	215.0 (44.7)	p = .876	*p = .040	p = .336
Radius Robustness Index	14.4 (2.9)	14.8 (2.9)	12.7 (3.1)	14.0 (4.1)	p = .838	p = .092	p = .335
Muscle Density (mgcm ³)	80.9 (1.9)	81.0 (2.1)	80.4 (1.1)	82.5 (1.7)	p = .043	p = .159	*p = .036
Muscle Area (cm ²)	31.4 (9.0)	23.8 (3.7)	28.4 (5.0)	21.3 (3.7)	p < .001	p = .201	p = .937
Subcutaneous Fat Area (cm ²)	3.3 (4.3)	8.7 (4.1)	12.0 (7.0)	10.3 (2.2)	p = .058	*p < .001	*p = .002
Cortical Density (mgcm ³)	860.9 (67.2)	886.3 (73.8)	894.1 (63.7)	874.5 (46.5)	p = .918	p = .071	p = .400
Cortical Area (mm ²)	105.5 (20.8)	95.7 (14.9)	93.4 (11.9)	92.7 (8.6)	p = .881	p = .243	p = .102
Volumetric densities							
Endo-cortical (mgcm ³)	998.2 (102.7)	1033.3 (93.7)	1034.7 (81.8)	1010.3 (51.5)	p = .771	p = .342	p = .370
Mid-cortical (mgcm ³)	1084.7 (107.0)	1136.2 (82.2)	1129.7 (57.7)	1149.6 (47.7)	*p = .032	*p = .010	p = .811
Peri-cortical (mgcm ³)	935.6 (101.6)	998.3 (72.1)	955.8 (63.1)	928.3 (61.9)	p = .178	p = .726	p = .067

Note. Pairwise comparisons are based on the estimated marginal means from the General Linear Model (GLM), controlling for age and bone length, and adjusting for multiple comparisons using Bonferroni correction. ***Bolded p < .05.**

LMC/DCD = Low Motor Competence / Developmental Coordination Disorder SD = standard deviation FMBU = Functional Muscle Bone Unit SSI = Stress Strain Index.

4. Discussion

The aim of the current study was to examine whether there were bone health differences in Australian adolescents with LMC/DCD when compared to typically developing age-matched Australian adolescents using pQCT data. Differences in bone parameters between Australian adolescents with LMC/DCD versus typically developing age-matched Australian adolescents described in this paper were similar to European normed between-group comparisons (Hands et al., 2015). New analyses based on sex revealed that Australian adolescent boys with LMC/DCD have less robust bones and higher subcutaneous fat than age-matched typically developing Australian boys, but no group differences were evident for adolescent girls. The sex interaction suggests a possible different mechanism for bone health development between boys and girls with LMC/DCD. This sex interaction has also been observed in the data from the Avon Longitudinal Study of Parents and Children (ALSPAC). A longitudinal analysis of the relationship between motor competence in early childhood and bone strength in late adolescence for all bone parameters, except for hip bone mineral density, found it to be strongest in males (Ireland et al., 2016) and young adults (Deere, Sayers, Rittweger, & Tobias, 2012).

As bone health is related to physical activity levels (Schoenau & Fricke, 2008; Tan et al., 2014), reduced physical activity levels in adolescents with DCD in comparison to typically developing peers (Cantell et al., 2008; Hands & Larkin, 2006; Zwicker et al., 2013) might be a contributing factor to poorer bone health. More specifically differences in bone health in adolescents may be due to a disparity between duration, frequency and load of physical activity necessary for bone development (Farr, 2011; Tan et al., 2014). Green et al. (2011) found that boys with DCD have lower moderate to vigorous physical activity levels compared to their typically developing male peers, but this difference was not found for girls. Heidemann et al. (2013) report a similar negative sex interaction between physical activity and bone when investigating the relationship between three categories of habitual physical activity (sedentary, low and moderate to high) with bone mineral content (DXA) in healthy children. Ireland et al. (2016) suggested that the relationship between motor competence and habitual loading through physical activity may be more important for boys. This has also been shown in young adults, where high and medium impact activity was positively associated with periosteal circumference in males, but not females (Deere et al., 2012a). In adolescents, a positive association between high levels of physical activity and hip bone mineral density has been reported, however tests for a gender interaction were not significant (Deere, Sayers, Rittweger, & Tobias, 2012).

Another possible explanation may lie in childhood physical activity behaviours before adolescence. Francis, Letuchy, Levy, and Janz, (2014) found that moderate-to-vigorous and vigorous-intensity physical activity at five years of age was a significant predictor of spine bone mineral density at 13 and 15 years of age, but only for boys. A more recent study found only pre-pubescent girls, but not boys, improved bone strength from an in-school physical education intervention (Fritz et al., 2016). It may be the types of activities that young girls are involved in are less likely to be associated with bone adaptation (Francis et al., 2014). A limitation to our current study was that actual physical activity levels for the LMC/DCD group were not measured. Physical activity data would enable the investigation of whether activities engaged in by girls with and without LMC/DCD is similar to that required for bone adaptation (ie. formation, regeneration and degradation of bone in response to mechanical load (Hart et al., 2017)). Further, differences between activity levels and types for boys with LMC/DCD and their typically developing peers who are reported to engage in more moderate to vigorous activity, rough and tumble play, and competitive sport could be explored.

Although in the current study, bone length was used as a proxy for pubertal status, a limitation was the lack of a direct measurement of pubertal and sex specific hormonal influences. It is possible, that the differences reported in this study for boys with

LMC/DCD may be related to sex specific hormonal differences between boys with LMC/DCD and typically developing male peers as pubertal maturation is critical in bone acquisition (Bonjour & Chevalley, 2014). For example, estradiol is important for accelerating bone maturation in girls, but has also been shown to play an important role in skeletal development for boys (Vandewalle et al., 2014). To the authors' knowledge no such studies have been reported comparing the DCD population (or LMC) with healthy peers with respect to sex specific hormonal differences. Overall, bone development during adolescence is multifactorial and likely involves epigenetic programming encompassing physiological variability, genetics, and environmental determinants such as diet and physical activity (Bonjour & Chevalley, 2014), factors beyond the scope of the current study.

For this study samples were drawn from two geographically different areas of Australia – Queensland and Western Australia, and it is not known whether this may be a factor in the differences observed. However considering that the results reported are similar to those originally found using European normative data, it would seem that this is unlikely to be the explanation for the identified sex interactions. Using an Australian sample as a comparison group with similar lifestyle, seasonal and cultural attributes is a study strength. Another strength of this study is the use of standardised measurement protocols and analytical approaches for bone analysis (Fonseca, Gordon, & Barr, 2013) although the slightly different voxel size between the control and LMC/DCD group scanners should be noted. For an unknown small number of participants with LMC/DCD, bone scans were conducted whilst they were enrolled in the exercise program. Given the temporal proximity of scans performed to enrolment date for most participants and the time-course of bone mechanoadaptation to exercise, it is unlikely this had any confounding influence on the data presented, and if anything, potentially underestimates the bone deficits observed in the LMC/DCD group. It should also be noted that the current sample includes a small number of participants who did not have a formal diagnosis of DCD, but the de-identified nature of the data did not permit these individuals to be identified and removed. Hence while results represent low motor competence, they may not be truly representative of a formally diagnosed DCD population.

In summary, the current study has important implications for the future bone health of adolescents with LMC/DCD, particularly boys. Specifically these results have identified many unanswered questions relating to the mechanisms underlying bone health for adolescent boys with LMC, which likely extends to the DCD population. It is necessary for future research to understand the specific mechanisms that may affect bone development in adolescents with DCD, and what interventions may reverse the higher bone health deficits observed, particularly for boys. Overall, any potential benefits identified for boys with DCD may also have applications to girls with DCD, adolescents with low motor competence and the broader adolescent community, especially as fracture incidence rates continue to rise disproportionately (Hedström, Svensson, Bergström, & Michno, 2010; Jenkins et al., 2018).

5. Conclusions

Comparisons of bone measures from adolescents with LMC/DCD with Australian comparative data are similar to European norm results revealing poorer bone health outcomes. However sex differences were found between boys and girls with LMC/DCD in the present study. Australian adolescent boys with LMC/DCD had less robust bones compared to Australian comparative data, whereas there were no between-group differences for girls. The mechanism which may explain these differences is not understood, but may be due to lower levels of habitual weight-bearing physical activity that is more distinct in adolescent boys compared to girls with LMC/DCD. Future research should examine these findings in a formally diagnosed DCD population as well as examine the impact of specific interventions that promote bone adaptation in girls and boys with LMC and specifically DCD. The development and implementation of such interventions may be particularly important during childhood, in order to optimise peak bone mass, and ultimately bone health across the lifespan.

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Declaration of interest

The authors declare no actual or potential conflict of interest including any financial, personal or other relationships with other people or organisations within three years of beginning the submitted work that could inappropriately influence, or be perceived to influence, their work.

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