European Journal of Sport Science
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tejs20

Radial bone size and strength indices in male road cyclists, mountain bikers and controls

Joanne A. Mcveigh[a], Rebecca Meiring[a], Alessandra Cimato[a], Lisa K. Micklesfield[b] & Tanja Oosthuyse[a]

[a] Exercise Laboratory, School of Physiology, Faculty of Health Sciences, University of Witwatersrand, Johannesburg, South Africa

[b] MRC/WITS Developmental Pathways for Health Research Unit, Department of Pediatrics, Faculty of Health Sciences, University of the Witwatersrand, Johannesburg, South Africa

Published online: 08 Jul 2014.

To cite this article: Joanne A. Mcveigh, Rebecca Meiring, Alessandra Cimato, Lisa K. Micklesfield & Tanja Oosthuyse (2014): Radial bone size and strength indices in male road cyclists, mountain bikers and controls, European Journal of Sport Science, DOI: 10.1080/17461391.2014.933881

To link to this article: http://dx.doi.org/10.1080/17461391.2014.933881

European Journal of Sport Science, 2014
http://dx.doi.org/10.1080/17461391.2014.933881

Routledge
Taylor & Francis Group

ORIGINAL ARTICLE

Radial bone size and strength indices in male road cyclists, mountain bikers and controls

JOANNE A. MCVEIGH[1], REBECCA MEIRING[1], ALESSANDRA CIMATO[1], LISA K. MICKLESFIELD[2], & TANJA OOSTHUYSE[1]

[1]*Exercise Laboratory, School of Physiology, Faculty of Health Sciences, University of Witwatersrand, Johannesburg, South Africa;* [2]*MRC/WITS Developmental Pathways for Health Research Unit, Department of Pediatrics, Faculty of Health Sciences, University of the Witwatersrand, Johannesburg, South Africa*

Abstract
Mountain biking (MB), unlike road cycling (RC) involves exposure to ground impact bone strain and requires upper-body muscle forces to maintain stability over uneven terrain and therefore may have differential effects on radial bone structure and strength. This study aimed to compare serum bone turnover marker concentration, 1-repetition maximum muscle strength and the radial proximal (diaphysis) and distal (metaphysis) bone structure [bone mineral content, total and cortical area (CoA), density and thickness, diameter and circumference], strength strain indices and muscle cross-sectional area (MCSA) using peripheral quantitative computed tomography (pQCT) between 30 male cyclists (18–34 years) MB (n = 10), RC (n = 10) and non-athletes controls (CON, n = 10). Differences were assessed by ANOVA and an ANCOVA (adjusting for body mass and height) where appropriate. MB radii were characterised by significantly stronger (14–16%), denser (9–27%) and larger (10%) metaphyses and stronger (22–23%) and larger (11–13%) diaphyses compared to RC and CON. RC had significantly 7% higher strength indices and 4% greater CoA and thickness than CON at the diaphysis, with no differences for other bone measurements. Serum C-terminal telopeptides of type-1 collagen concentration (bone resorption marker) was higher in RC than MB ($p < 0.05$) and above the age-reference range. MCSA and strength were greater in MB than RC ($p < 0.05$). Muscle forces generated during RC appear to produce an osteogenic stimulus to increase radial bone strength indices with minimal improvement in bone structure. However greater resorptive activity in RC suggests inadequate loading to support bone maintenance. In conclusion, bone loading, muscle size and strength of MB are superior to RC.

Keywords: *pQCT, cyclists, bone strength*

Introduction

Notwithstanding the high risk nature of cycling that predisposes participants to traumatic fractures, road cycling (RC) has also been thought to offer no significant osteogenic benefit (Olmedillas, González-agüero, Moreno, & Casajus, 2012). The two types of endurance cycling [RC and mountain biking (MB)] confer different types and magnitudes of mechanical loads on the bone (Warner, Shaw, & Dalsky, 2002). The lack of impact from smooth surface cycling and the rhythmical pedalling action requiring long bouts of repetitive, low-force muscle contractions in a body mass supported activity appear to be the main reason for the low bone mass observed in road cyclists (Prioreschi, Oosthuyse, Avidon, & McVeigh, 2012; Warner et al., 2002). Conversely, MB may impose an osteogenic stimulus and this may be largely attributable to greater ground surface-induced loads owing to the rougher terrain involved (De Lorenzo & Hull, 1999). Additionally, mountain bikers spend more time with two points in bicycle contact (hands and feet) instead of three contact points (seat, hands and feet) as observed in road cyclists, causing greater loading through the appendicular skeleton (Wang & Hull, 1997).

Bone is dynamic, constantly being remodelled according to the strain placed on it. Strain below a minimum threshold will cause bone resorption, and above it will cause deposition of new bone (Frost, 2003; Lanyon & Rubin, 1984). Athletes participating in sports which expose them to high magnitude

Correspondence: Joanne A. McVeigh, Exercise Laboratory, School of Physiology, Faculty of Health Sciences, University of Witwatersrand, Johannesburg 2000, South Africa. E-mail: Jo-anne.McVeigh@wits.ac.za

impact strains (gymnasts, soccer players, hurdlers and runners) have repeatedly been shown to have stronger bones than controls at the loaded skeletal sites (Nikander, Sievänen, Uusi-Rasi, Heinonen, & Kannus, 2006). Conversely, studies which have used dual-energy X-ray absorptiometry (DXA) to assess bone mass suggest that road cyclists have lower, or comparable, spine and hip areal bone mineral density (aBMD) compared with controls (Nichols, Palmer, & Levy, 2003; Olmedillas et al., 2012; Stewart & Hannan, 2000; Warner et al., 2002). Furthermore, data are scarce on mountain bikers. Only one study has compared areal bone mass between MB and RC and concluded that MB provides an osteogenic stimulus in adult males (Warner et al., 2002).

Much of the data for cyclists have been obtained from DXA, which provides two-dimensional information on the bone, and the consensus from these studies is that RC appears to offer no benefit or in fact negatively affects aBMD in healthy males in spite of the powerful muscle contractions involved in the sport (Campion et al., 2010; Olmedillas et al., 2012). A newer bone imaging tool – peripheral quantitative computed tomography (pQCT) – offers three-dimensional information on bone by evaluating bone size, geometry and strength. Specifically, pQCT evaluates volumetric bone mineral density (BMD) and is able to distinguish between cortical and trabecular bone (Dowthwaite et al., 2009).

In accordance with the mechanostat theory (Frost, 2004), Wilks, Gilliver, and Rittweger (2009) hypothesised that during cycling, the appendicular skeleton is in fact exposed to large muscle forces at fast speeds, and therefore there should be an osteogenic response (Wilks et al., 2009). Using pQCT, Wilks et al. reported greater bone mineral content (BMC), area and strength at tibia and radius in male track cyclists compared to controls and concluded that track cycling is beneficial in preserving bone health. Thus, despite road cyclists having lower spine and hip bone mass (as measured by DXA) than sedentary controls and mountain bikers (Olmedillas et al., 2012), bone mass may be preserved at appendicular sites such as the radius. No study that we are aware of has compared differential long-term effects of regular RC and MB on radial bone strength, structure and geometry using pQCT. Furthermore, muscle mass is a determinant of BMD in cyclists (Rector, Rogers, Ruebel, & Hinton, 2008), and improved limb strength and cycling power is associated with an increase in muscle cross-sectional area (MCSA); (Rønnestad, Hansen, & Raastad, 2010). Thus, it is also necessary to determine whether the distinct differences in upper-body strength that characterise RC and MB, including the absence or presence of ground impact forces and low or high level of upper-body muscle control needed to maintain stability on the bike, respectively, will result in a notable difference in muscle hypertrophy and strength in the radius.

We hypothesise that mountain bikers have greater upper limb bone size and strength indices and greater upper limb MCSA and strength compared to road cyclists. Previous exercise-induced bone adaptations assessed using pQCT have been mostly evident in the diaphyses of the limbs, areas of predominantly cortical bone (Heinonen, Sievänen, Kannus, Oja, & Vuori, 2002; Wilks et al., 2009). Therefore, the aims of the current study were to use pQCT to compare diaphyseal (proximal) and metaphyseal (distal) radial bone size and strength between trained male road cyclists and mountain bikers, and to compare them to sedentary control participants. We also aimed to compare MCSA and arm strength between road cyclists and mountain bikers.

Methods

Participants

All participants were healthy, non-smoking, 18- to 34-year-old men, who were screened for medical and medication history that could adversely affect bone health. All cyclists were recruited first and then sedentary control participants who met inclusion criteria were matched as closely as possible to the cyclists by age. Ten of the cyclists were trained for distance road racing (RC), and 10 were trained for distance MB events. Cyclists who engaged in any cross-training (i.e., non-cycling weight-bearing activity including resistance training) within the previous three years were excluded from the study. Sedentary control participants (CON, n = 10) performed two hours or less of structured physical activity per week. Each volunteer provided written informed consent and the study was approved by the Human Research Ethics Committee of the University of the Witwatersrand (protocol no.: M090558) which adheres to the principles of the 1964 Declaration of Helsinki and its later amendments.

Dietary analysis

All participants completed a calcium intake questionnaire rapid assessment for a typical day of the week. This allowed for analysis of the average calcium intake in a typical 24-hours period and has been used previously in athletes and was found to be reliable and valid (Ward et al., 2004). Calcium intakes were assessed with NAT.2 software ("Nutritional Access Tool", 2013, USA), which was used to calculate an estimate of the amount of calcium consumed per day (mg).

Physical activity and training history

The Global Physical Activity Questionnaire (GPAQ) was used to assess the physical activity of the cyclists and controls (data not shown). Specifically, the information gathered from the "recreational activities" and "sedentary behaviour" components of the GPAQ were used to define the control group's sedentariness. The World Health Organization developed the GPAQ to measure the PA habits of populations using a standardised protocol (Bull, Maslin, & Armstrong, 2009). Hours of training per week and sports-specific training histories were ascertained from cyclists only. Control participants were mentally active, as evidenced by occupation or educational participation, but participated in little or no physical activity: less than two hours of endurance exercise per week, no exhaustive and no resistive exercise. This was assessed by a verbal conversation along with a personal interview and administration of the GPAQ.

Anthropometry

Body height (to the nearest cm) and mass (to the nearest 100 g) were measured with a wall-mounted stadiometer and digital weigh scale (Holtain, UK), respectively. Both measurements were taken with participants wearing short pants only and without shoes. Body mass index (BMI) was calculated as body mass/height squared (kg/m^2). Ulna length was measured from the olecranon process to the styloid process of the ulna using sliding calliper's (Holtain, Crosswell, UK) to the nearest mm for pQCT measurements. All devices were routinely calibrated throughout the study.

Body composition

All participants underwent a whole body DXA scan (Hologic QDR 4500A, Hologic, Boston, MA, USA) performed by a qualified technician for the assessment of lean and fat tissue mass.

Upper-body muscle strength

Upper-body one repetition maximum test (1-RM) was determined using a T-bar. Only the MB and RC groups completed the test to measure upper-body strength after completing a standard warm-up. The upper-body 1-RM was performed with the participant positioned on a T-bar row machine with the chest against a bench at a 45° angle, grasping the handles with each hand using an overhand grip. To complete the test the participant disconnects the bar from its locked position and lets it hang straight down, so that the arms are fully extended. The participant then lifts or rows the bar up to the chest area, and then returns to the start position. All testing procedures were conducted following the American College of Sports Medicine Guidelines for the 1-RM test. Each cyclist performed a standard warm up before completing a 1-RM for the determination of upper-body strength. An initial weight was chosen that was within the participants perceived capacity. Resistance was progressively increased until the participant could not complete the selected repetition through the full range of motion, while maintaining the correct posture. If the participant failed to maintain the correct posture or could not lift the weight through the full range of motion then the previous trial was recorded as the 1-RM. The final weight lifted successfully was recorded as the 1-RM. Standard procedures were followed whereby 1-RM was determined within four trials with 3- to 5-minute rest periods between trials. All cyclists performed the 1-RM test in a single visit to the laboratory.

Biochemical markers of bone metabolism

A 10 mL blood sample was collected from all cyclists (n = 20) via the antecubital vein by a trained phlebotomist in the early morning (prior to 10 am), after an overnight fast. Participants were instructed to refrain from exercise during the 24 hours prior to blood collection. Blood was dispensed into serum separator tubes and allowed to coagulate at room temperature. Serum was obtained through centrifugation and then stored at −80°C until analyzed. All bone turnover marker assessments were done in duplicate, and all assays were performed in a single run to eliminate inter-assay variability. Serum C-terminal telopeptides of type-1 collagen (CTX) were measured as a marker of bone resorption by way of commercially available immunoenzymatic assay (Serum CrossLaps ELISA, Immuno Diagnostic Solutions, UK). Bone-specific alkaline phosphastase (Bone-AP) was measured as a marker of bone formation with a commercially available immunoenzymatic assay (Ostase BAP, Immuno Diagnostic Solutions, UK).

Musculoskeletal parameters

Measures of the non-dominant forearm were performed using pQCT (Stratec XCT 2000, Stratec Medical, Pforzheim, Germany). A scout view was performed for each subject and a reference line placed at the midline of the epiphyseal plate of the radius. Scans, 2.3 mm thick, were obtained at 4% and 65% of the length of the radius from the reference lines. The following measures were obtained from the metaphysis of the radius (4%

slice): total cross-sectional area (ToA, mm^2), total volumetric density (ToD, mg/cm^3) and trabecular density (TrbD, mg/cm^3). From the 65% site, the following measures were obtained: polar strength strain index (SSIp, mm^3), BMC, g/cm, cortical density (CoD, mg/cm^3), total area (ToA, mm^2), cortical area (CoA, mm^2) and MCSA, mm^2. Periosteal circumference (PC, mm), endosteal diameter (ED, mm), radial diameter (RD) and cortical thickness (CT, mm) were calculated using formulas previously described (Kontulainen, Sievänen, Kannus, Pasanen, & Vuori, 2003; Micklesfield, Norris, & Pettifor, 2011). Participants were asked to lie as still as possible while being scanned and if there were significant motion artefacts whereby an acceptable reading could not be obtained, the scan was repeated. For the cortical and bone geometry measures at the 65% radial site, bone threshold was set at 711 mg/cm^3 (contour mode 1/peel mode 2). Threshold for SSIp was set at 480 mg/cm^3. MCSA (cm^2) and fat cross-sectional area (FCSA, cm^2) were determined at the 65% radial site as this site is associated with the largest muscle belly. Subcutaneous FCSA was analysed using contour mode 3 and calculated as the area with a density below 40 mg/cm^3. MCSA was also analysed using contour mode 3 and was calculated as the area with a density between 40 and 180 mg/cm^3. For the measures of MCSA, threshold was set at 40 mg/cm^3 (contour mode 3/peel mode 1). The same independent technician performed and analyzed all pQCT scans and was blinded to the grouping of the participants. A QC phantom spine was scanned each morning and the CV for total attenuation for repeat scans on the spine phantom was 0.44% and trabecular attenuation was 0.37% during the study period.

Statistical analyses

Descriptive summary statistics were calculated using means and SD or, in the case of figures, ratios of the cyclists' and controls' bone measures along with confidence intervals (CI). All data were assessed for normality using the Shapiro–Wilk statistic. Differences in both anthropometric variables between the groups (road cyclists, mountain bikers and controls) were assessed by ANOVA. A multivariate analysis of covariance (MANCOVA) was used to compare musculoskeletal measure between the groups, after adjusting for body mass and height. The false discovery rate procedure was applied to the *F*-statistic to control for multiple comparison bias when evaluating a family ($k = 13$) of related bone variables (Curran-Everett, 2000). Bonferroni post hoc analysis was performed when a significant overall effect was detected. Cohen's *d* effect size was derived to describe the magnitude of effect, where accordingly as effect size is ranked as: 0.0–0.02, trivial; 0.2–0.6, small; 0.6–1.2, moderate; 1.2–2.0, large; 2.0–4.0, very large; and > 4.0, extremely large effects (Hopkins, Marshall, Batterham, & Hanin, 2009). Statistical analyses were performed using SPSS version 21.0 (SPSS, Chicago, IL, USA) and significance was accepted at an alpha level of $p \leq 0.05$.

Results

Anthropometric, muscle strength and bone turnover characteristics

Age, body height, body mass, limb length, lean mass and calcium intake were comparable between the all groups (Table I). Controls had a significantly greater percentage body fat than both cycling groups

Table I. Descriptive characteristic of participants

	MB	RC	CON
n	10	10	10
Age (years)	26.0 (5.8)	22.9 (3.4)	26.9 (5.5)
Height (m)	1.77 (0.04)	1.79 (0.06)	1.75 (0.06)
Body mass (kg)	76.7 (7.1)	71.5 (6.6)	77.8 (17.4)
BMI (kg/m^2)	24.4 (2.6)	22.2 (1.1)	25.4 (6.0)
Radius length (mm)	292 (14)	289 (11)	281 (9)
Lean body mass (kg)	63.4 (4.3)	60.4 (4.5)	59.4 (9.9)
Body fat (%)	12.8 (4.4)[a]	11.9 (2.9)[a]	19.3 (6.3)
Daily calcium intake (mg/day)	1706 (504)	2079 (1372)	1622 (731)
Athlete characteristics			
Bone-AP (U/L)	24.19 (12.52)	18.55 (14.05)	–
CTX (ng/ml)	0.45 (0.20)	0.74 (0.30)[b]	–
Upper-body 1-RM (kg)	71.0 (12.0)[b]	59.9 (11.7)	–
Involvement in sport (years)	5.8 (4.8)	6.4 (3.6)	–
Training (hours/wk)	13.6 (4.6)	13.5 (6.2)	–

[a]Different to CON; [b]difference between RC and MB.
Data are mean (SD).
BMI, body mass index; CTX, serum C-terminal telopeptides of type-1 collagen.

Table II. Comparison of radial bone variables between cyclists after adjusting for weight and height

	Mean (SE)			[a]Cohen's *d* effect size		
	MB	RC	CON	MB–RC	MB–CON	RC–CON
65% Radius (diaphysis)						
BMC (mg)	1.41 (0.02)	1.24 (0.02)[b]	1.20 (0.04)	2.69	2.10	0.40
ToA (mm^2)	192.03 (9.91)	162.53 (5.26)[b]	160.08 (6.49)	1.18	1.21	0.13
CoA (mm^2)	109.15 (4.33)	96.17 (2.90)[b]	92.18 (3.42)	1.11	1.38	0.40
CoD (mg/mm^3)	1139.08 (13.03)	1147.23 (9.44)	1146.35 (6.37)	−0.23	−0.22	0.03
CT (mm)	2.70 (0.06)	2.60 (0.10)[b]	2.51 (0.04)	0.38	1.19	0.37
ED (mm)	10.21 (0.40)	9.16 (0.32)[b]	9.21 (0.22)	0.92	0.98	−0.06
RD (mm)	15.61 (0.42)	14.36 (0.22)[b]	14.23 (0.28)	1.18	1.22	0.16
PC (mm)	49.03 (1.32)	45.10 (0.69)[b]	44.68 (0.88)	1.18	1.23	0.17
SSIp (mm^3)	483.45 (32.91)	391.99 (20.60)[b]	363.58 (19.75)	1.05	1.40	0.45
Muscle CSA (mm^2)	4963.62 (55.36)	4468.06 (58.01)[b]	4469.80 (135.57)	2.76	1.51	−0.01
Fat CSA (mm^2)	570.75 (64.21)	529.78 (27.43)	882.33 (142.87)	0.26	−0.89	−1.08
4% Radius (metaphysis)						
ToA (mm^2)	423.82 (4.91)	385.42 (9.21)[b]	384.50 (10.47)	1.65	1.52	0.03
ToD (mg/mm^3)	427.23 (3.02)	401.96 (4.50)[b]	390.00 (4.76)	2.09	2.95	0.82
TrbD (mg/mm^3)	255.56 (12.03)	237.46 (14.14)	200.10 (11.34)	0.44	1.50	0.92
BSI (mm^3)	872.70 (6.97)	762.21 (11.35)[a]	752.71 (16.71)	3.71	2.96	0.21

[a]Cohen's *d* effect size score describes the magnitude of an effect and is ranked as: 0–0.2, trivial; 0.2–0.6, small; 0.6–1.2, moderate; 1.2–2.0, large; 2.0–4.0, very large; >4.0, extremely large effects (Hopkins et al., 2009). The column MB–RC, MB–CON and RC–CON show the standardised effect size scores between mountain bikers and road cyclists; mountain bikers and controls; and road cyclists and controls, respectively; [b]Difference between RC and MB.
Data are means (SE).
BMC, bone mineral content; ToA, total area; CoA, cortical area; CoD, cortical bone mineral density; CT, cortical thickness; ED, endosteal diameter; RD, radial diameter; PC, periosteal circumference; SSIp, polar strength strain index; CSA, cross-sectional area; ToD, total bone mineral density; TrbD, trabecular bone mineral density; BSI, bone strength index.

($p < 0.01$). Serum bone-AP concentration was not different between the cycling groups, but serum CTX concentration was significantly higher in RC than MB ($p = 0.037$; Table I). MB had greater ($p = 0.051$) 1-RM for upper-body strength than the RC group (Table I). Training volume was comparable between the road and mountain bike cyclists and the two groups of cyclists were well matched for the number of years that they had been involved in the sport.

Absolute group differences of radial bone measures between cyclists

At the 65% site (diaphysis), and after adjustment for body mass and height, MB had significantly greater radial BMC, ToA, CoA, CT, RD, PC, SSIp and CSMA than RC (all $p < 0.05$; Table II). There were no differences between FCSA of the two groups of cyclists ($p = 0.09$). At the 4% site (metaphysis), MB had a greater ToA, ToD and BSI than did RC ($p < 0.01$; Table II).

Percentage difference in bone measure relative to sedentary controls

The body mass and height-adjusted diaphyseal radial (Figure 1A) and metaphyseal radial (Figure 1B) pQCT measures for the cyclists were expressed as a percentage difference in relation to sedentary referents (controls). At the diaphyseal site, radial BMC, ToA, CoA, SSIp, PC, ED, CT and MCSA were 10–33% greater in MB compared to the controls (all p values < 0.05). RC had greater radial CoA (4%), SSIp (8%) and CT (3%) than CON ($p < 0.05$). Both MB and RC had significantly less FCSA (−35 to −40%) than CON. At the metaphysis, both MB and RC had significantly greater total and TrbD (3–19%) than CON, whereas MB also had significantly greater ToA (10%) and BSI (16%) than CON.

Discussion

The primary aim of this study was to compare radial bone measures, using pQCT, between mountain bikers, road cyclists and physically inactive controls. As hypothesised, mountain bikers had greater bone content, size and strength at the radius and greater limb strength and upper-body MCSA than both road cyclists and controls. Of particular interest are the larger forearm bone strength indices and CT in the road cyclists compared to the controls which were most evident at the diaphysis, suggesting that exercise-specific adaptations of bone may indeed occur in the absence of impact forces, but in the presence of forceful muscle contractions.

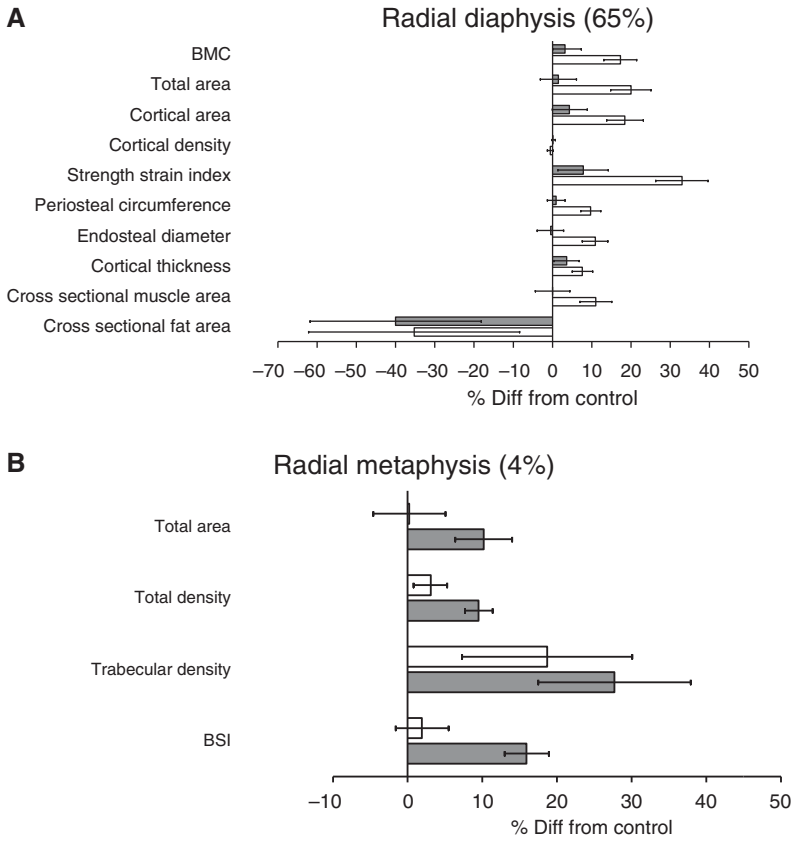

Figure 1. Percentage differences and 95% CI of radial diaphysis (panel A) and radial metaphysis (panel B) measures of road cyclists (grey bars) and mountain bikers (white bars), compared with the sedentary controls. Note that when the CI does not contain a zero, the variable is significantly different to the control group. Data are adjusted for body mass and height.

To our knowledge, only one study has used pQCT to assess musculoskeletal parameters in cyclists (Wilks et al., 2009). Although reviews of bone health in cyclists suggest that cycling is not osteogenic (Nagle & Brooks, 2011; Olmedillas et al., 2012; Scofield & Hecht, 2012), the findings of the current study and the study by Wilks et al. indicate this may not necessarily be so at peripheral or appendicular sites which are not routinely measured with traditional scanning methods such as DXA. Specifically, Wilks and colleagues reported between 8–13% larger CoA, BMC and strength strain index at the radius of master sprint track cyclists compared to controls, but no difference in radial bone measures in the distance track cyclists compared to controls (Wilks et al., 2009). In the current study, both mountain bikers and to a lesser degree road cyclists, displayed greater radial bone strength strain indices, CoA and CT compared to sedentary controls (8–33% in MB and 3–8% in RC), as well as greater bone size measures (BMC, ToA, periosteal and endosteal circumferences) only evident in the mountain bikers. However, it must be noted that the study of Wilks et al. included older athletes who had a much longer cycling history compared to the young cyclists in the current study who had only ~6 years of cycling experience. The improved radial bone strength indices and structure in all types of cycling may be a consequence of bone strain imposed through muscle force generation in the forearm to support the upper-body mass in the semi-prone posture through the arms resting on the handlebars. Further, the generation of muscle forces to accomplish breaking and steering actions as well as counteractive forces to hold the body still and in place against the forward propulsion generated by leg muscle contraction (Wilks et al., 2009) may act in an osteogenic manner. Furthermore, the greater osteogenic stimulation during MB in the radius compared to RC can be explained by the additional expected loading exerted at the handlebars (>1.2 × relative to static loading) and front wheel (3 × the body mass of the rider) due to the imposed ground reaction forces experienced during MB (De Lorenzo & Hull, 1999).

Although data on bone health in mountain bikers are limited, findings from Warner et al. suggest that bone mass (as measured by DXA) at the lumbar spine, hip and whole body is higher in mountain bikers compared to road cyclists (Warner et al., 2002). The high-intensity nature of MB requires riders to endure steep climbs and undergo isometric contractions of arm and leg muscles in order for

stabilisation on the bicycle to be achieved while negotiating uneven ground surfaces (Impellizzeri & Marcora, 2007). In this respect, the greater indices of bone strength and structure observed in the mountain bikers compared to road cyclists coincides together with a greater MCSA, suggests muscle hypertrophy in response to the generation of larger muscle forces. The difference in muscle strength is further supported by the significantly higher 1-RM scores of the mountain bikers compared to road cyclists. The different demands from the uneven terrain to which mountain and road cyclists are exposed may further contribute to the observed differences in upper-body strength. Verification of these finding with the previous study of Warner et al. (2002) is difficult, as while they report no difference in absolute leg strength (N) and power (W) measured by leg extension 1-RM between road and mountain bike cyclists, they did not correct for the significantly lower body weight of the mountain bikers. A structurally superior bone is not necessarily attributable to more BMC, but is also highly related to architectural adaptations such as an enlarged cross-sectional area or greater CT (Nikander et al., 2006). Accordingly, the larger strength strain index in the cycling groups may be due to the greater CT observed in both groups and the larger CoA in the mountain bikers. Consistent with the previous finding that exercise-induced bone gain occurs by enlargement of bone size with no change in volumetric bone density in weight-bearing athletes (Haapasalo et al., 2000), the current study also found no difference in cortical volumetric density of the radius in both mountain bikers and road cyclists compared to the controls despite obviously larger bones, particularly in the mountain bikers. Although there is no conclusive evidence that muscle or gravitational force play a more important role in enhancing bone mass (Kohrt, Barry, & Schwartz, 2009), the larger strength strain indices for cyclists at the diaphysis of the radius may be partially attributable to the tightly coupled muscle bone unit. In a study by Nikander et al., loading-related differences in bone strength indices were assessed in athletes participating in impact, weight-bearing and non-impact, non-weight bearing sports. In their study, swimmers were found to have 19% greater strength strain indices than controls. The authors suggested that muscle performance related to high joint moments were responsible for increased strength observed in the humerus of swimmers (Nikander et al., 2006). Even though muscle size of the road cyclists in our study, was not necessarily larger than controls there is evidence that bone may respond to muscle forces that are below the threshold necessary to induce muscular hypertrophy (Kohrt et al., 2009). Similar to the road cyclists in our study, swimming involves vigorous muscle activity in the absence of impact or weight-bearing and thus it is plausible to attribute stronger bones to the muscle forces being generated during cycling. The significantly higher serum CTX concentration, indicative of bone resorption activity, in the road cyclists compared to mountain bikers is noteworthy. In fact, the serum CTX concentration observed in the road cyclists is above the normal population reference range reported for similar-age Australian males (20–29 years: 0.45–0.68 $ng{\cdot}ml^{-1}$ and 30–39 years: 0.28–0.47 $ng{\cdot}ml^{-1}$; Jenkins et al., 2013). Furthermore, while a previous study found 24-hours resting urine CTX to be unchanged, serum bone-AP concentration as a marker of bone formation was less in cyclists compared to other athletes or controls (Maïmoun et al., 2004). Moreover, previous studies in road cyclists have found markers of bone resorption to be increased immediately following a single bout of stationary cycling (Barry et al., 2011; Guillemant, Accarie, Peres, & Guillemant, 2004; Herrmann, Mu, Sand-hill, & Herrmann, 2007). Our laboratory has recently found that this immediate post-cycling bone resorption marker response is suppressed after the third and fourth consecutive day of prolonged cycling (Oosthuyse, Badenhorst, & Avidon, 2014), a prevalence favouring bone resorption dominance continues to persist following overnight recovery on all successive days of cycling (Lombardi et al., 2012; Oosthuyse et al., 2014). Thus, bone marker concentrations measured in our study provide insight regarding whole-body skeletal metabolism and suggest that RC promotes a disproportionate increase in bone resorption. Other factors that stimulate bone resorption during or following exercise, such as, the calciotropic hormonal response to calcium lost during prolonged sweating (Barry & Kohrt, 2007) and the metabolic stress of intense endurance cycling (Lombardi et al., 2012), are similar for both RC and MB and therefore cannot explain the greater resorption activity observed in road cyclists. Therefore, while the findings of the current study suggest that bone torsion due to repetitive muscle contraction in RC does impose some osteogenic activity in the appendicular skeleton and is associated with greater bone strength strain indices at the sites of contractile activity, the accumulative bone strain may be below the threshold required for bone maintenance due to the presence of increased bone resorption (Frost, 2004).

This study has limitations. Although our sample size was small, a sample size calculation showed that at a 5% level (using an SD of 65 mm^3), we would require a sample size of six participants per group for a difference of 20% in SSIp to be detected. Nonetheless, our cross-sectional study design limits the inferences that we can draw. Additionally our study

was conducted in males only and thus (although plausible), our results may not necessarily be extended to females. We did not collect force data in this study, so it is not known whether the cyclists studied experienced the same magnitudes of force described elsewhere (De Lorenzo & Hull, 1999; Jeukendrup, Craig, & Hawley, 2000). We also acknowledge that muscle strength and bone formation and resorption markers in the control group would have further supported our findings. The possibility of self-selection bias is a concern in cross-sectional studies of adult athletes and we therefore acknowledge that individuals with initially better physical capability may be more likely to participate in athletic activities.

In conclusion, contrary to previous reports of low BMD and bone strength indices at the axial skeleton in road cyclists, the current study with the use of pQCT, found that road cyclists appear to have stronger radial diaphyses compared to those with a sedentary lifestyle; albeit with minimal advantage in bone structure and increased blood markers suggestive of bone resorption activity. Furthermore, we found that MB, which imposes bone strain through both ground reaction force and muscle contraction, may produce a superior osteogenic stimulus for gain in bone size and strength of the radius than RC. Moreover, MB is associated with greater exercise-induced muscle hypertrophy and upper-body strength compared to RC in amateur athletes.

References

Barry, D. W., Hansen, K. C., van Pelt, R. E., Witten, M., Wolfe, P., & Kohrt, W. M. (2011). Acute calcium ingestion attenuates exercise-induced disruption of calcium homeostasis. *Medicine and Science in Sports and Exercise*, *43*, 617–23. doi:10.1249/MSS.0b013e3181f79fa8

Barry, D. W., & Kohrt, W. M. (2007). Acute effects of 2 hours of moderate-intensity cycling on serum parathyroid hormone and calcium. *Calcified Tissue International*, *80*, 359–65. doi:10.1007/s00223-007-9028-y

Bull, F. C., Maslin, T. S., & Armstrong, T. (2009). Global physical activity questionnaire (GPAQ): Nine country reliability and validity study. *Journal of Physical Activity and Health*, *6*, 790–804.

Campion, F., Nevill, A. M., Karlsson, M. K., Lounana, J., Shabani, M., Fardellone, P., & Medelli, J. (2010). Bone status in professional cyclists. *International Journal of Sports Medicine*, *31*, 511–515. doi:10.1055/s-0029-1243616

Curran-Everett, D. (2000). Multiple comparisons: Philosophies and illustrations. *American Journal of Physiology*, 279 (1), R1–R8.

De Lorenzo, D., & Hull, M. (1999). Quantification of structural loading during off-road cycling. *Journal of Biomechanical Engineering*, *121*, 405.

Dowthwaite, J. N., Hickman, R. M., Kanaley, J. A., Ploutz-Snyder, R. J., Spadaro, J. A., & Scerpella, T. A. (2009). Distal radius strength: A comparison of DXA-derived vs. pQCT-measured parameters in adolescent females. *Journal of Clinical Densitometry: The Official Journal of the International Society for Clinical Densitometry*, *12*(1), 42–53. doi:10.1016/j.jocd.2008.06.001

Frost, H. M. (2003). Bone's mechanostat: A 2003 update. *The A natomical Record. Part A: Discoveries in Molecular, Cellular, and Evolutionary Biology*, *275*, 1081–1101. doi:10.1002/ar.a.10119

Frost, H. M. (2004). A 2003 update of bone physiology and Wolff's law for clinicians. *Angle Orthodontist*, *74*(1), 3–15.

Guillemant, J., Accarie, C., Peres, G., & Guillemant, S. (2004). Acute effects of an oral calcium load on markers of bone metabolism during endurance cycling exercise in male athletes. *Calcified Tissue International*, *74*, 407–414. doi:10.1007/s00223-003-0070-0

Haapasalo, H., Kontulainen, S., Sievänen, H., Kannus, P., Järvinen, M., & Vuori, I. (2000). Exercise-induced bone gain is due to enlargement in bone size without a change in volumetric bone density: A peripheral quantitative computed tomography study of the upper arms of male tennis players. *Bone*, *27*, 351–357. doi:10.1016/S8756-3282(00)00331-8

Heinonen, A., Sievänen, H., Kannus, P., Oja, P., & Vuori, I. (2002). Site-specific skeletal response to long-term weight training seems to be attributable to principal loading modality: A pQCT study of female weightlifters. *Calcified Tissue International*, *70*, 469–474. doi:10.1007/s00223-001-1019-9

Herrmann, M., Mu, M., Sand-hill, M., & Herrmann, W. (2007). The effect of endurance exercise-induced lactacidosis on biochemical markers of bone turnover. *Clinical Chemistry and Laboratory Medicine*, *45*, 1381–1389. doi:10.1515/CCLM.2007.282

Hopkins, W. G., Marshall, S. W., Batterham, A. M. & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, *41*(1), 3–12. doi:10.1249/MSS.0b013e31818cb278

Impellizzeri, F. M., & Marcora, S. M. (2007). The physiology of mountain biking. *Sports Medicine*, *37*(1), 59–71. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/17190536

Jenkins, N., Black, M., Paul, E., Pasco, J. A., Kotowicz, M. A., & Schneider, H.-G. (2013). Age-related reference intervals for bone turnover markers from an Australian reference population. *Bone*, *55*, 271–276. doi:10.1016/j.bone.2013.04.003

Jeukendrup, A., Craig, N., & Hawley, J. (2000). The bioenergetics of world class cycling. *Journal of Science and Medicine in Sport*, *3*, 414–433. doi:10.1016/S1440-2440(00)80008-0

Kohrt, W. M., Barry, D. W., & Schwartz, R. S. (2009). Muscle forces or gravity: What predominates mechanical loading on bone? *Medicine and Science in Sports and Exercise*, *41*, 2050–2055. doi:10.1249/MSS.0b013e3181a8c717

Kontulainen, S., Sievänen, H., Kannus, P., Pasanen, M., & Vuori, I. (2003). Effect of long-term impact-loading on mass, size, and estimated strength of humerus and radius of female racquet-sports players: A peripheral quantitative computed tomography study between young and old starters and controls. *Journal of Bone and Mineral Research*, *18*, 352–359. doi:10.1359/jbmr.2003.18.2.352

Lanyon, L., & Rubin, C. (1984). Static vs. dynamic loads as an influence on bone remodelling. *Journal of Biomechanics*, *12*(89), 105. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/4077869

Lombardi, G., Lanteri, P., Graziani, R., Colombini, A., Banfi, G., & Corsetti, R. (2012). Bone and energy metabolism parameters in professional cyclists during the Giro d'Italia 3–weeks stage race. *PLoS One*, *7*(7), e42077. doi:10.1371/journal.pone.0042077

Maïmoun, L., Mariano-Goulart, D., Couret, I., Manetta, J., Peruchon, E., Micallef, J. P., … Leroux, J. L. (2004). Effects of physical activities that induce moderate external loading on bone metabolism in male athletes. *Journal of Sports Sciences*, *22*, 875–883. doi:10.1080/02640410410001716698

Micklesfield, L. K., Norris, S. A., & Pettifor, J. M. (2011). Determinants of bone size and strength in 13–year–old

South African children: The influence of ethnicity, sex and pubertal maturation. *Bone*, *48*, 777–85. doi:10.1016/j.bone.2010.12.032

Nagle, K. B., & Brooks, M. A. (2011). A systematic review of bone health in cyclists. *Sports Health*, *3*, 235–243. doi:10.1177/1941738111398857

Nichols, J. F., Palmer, J. E., & Levy, S. S. (2003). Low bone mineral density in highly trained male master cyclists. *Osteoporosis International: A Journal Established as Result of Cooperation between the European Foundation for Osteoporosis and the National Osteoporosis Foundation of the USA*, *14*, 644–649. doi:10.1007/s00198-003-1418-z

Nikander, R., Sievänen, H., Uusi-Rasi, K., Heinonen, A., & Kannus, P. (2006). Loading modalities and bone structures at nonweight-bearing upper extremity and weight-bearing lower extremity: A pQCT study of adult female athletes. *Bone*, *39*, 886–94. doi:10.1016/j.bone.2006.04.005

Olmedillas, H., González-agüero, A., Moreno, L. A., & Casajus, J. A. (2012). Cycling and bone health: A systematic review. *BMC Medicine*, *10*(168), 1–10. doi:10.1186/1741-7015-10-168

Oosthuyse, T., Badenhorst, M., & Avidon, I. (2014). Bone resorption is suppressed immediately after the 3rd and 4th day of multiday cycling but persistently increased following overnight recovery. *Applied Physiology, Nutrition, and Metabolism*, *39*, 64–73. doi:10.1139/apnm-2013-0105

Prioreschi, A., Oosthuyse, T., Avidon, I., & McVeigh, J. (2012). Whole body vibration increases hip bone mineral density in road cyclists. *International Journal of Sports Medicine*, *33*, 593–599. doi:10.1055/s-0032-1301886

Rector, R. S., Rogers, R., Ruebel, M., & Hinton, P. S. (2008). Participation in road cycling vs. running is associated with lower bone mineral density in men. *Metabolism: Clinical and Experimental*, *57*, 226–32. doi:10.1016/j.metabol.2007.09.005

Rønnestad, B. R., Hansen, E. A., & Raastad, T. (2010). Effect of heavy strength training on thigh muscle cross-sectional area, performance determinants, and performance in well-trained cyclists. *European Journal of Applied Physiology*, *108*, 965–975. doi:10.1007/s00421-009-1307-z

Scofield, K. L., & Hecht, S. (2012). Bone health in endurance athletes: Runners, cyclists, and swimmers. *Current Sports Medicine Reports*, *11*, 328–334. doi:10.1249/JSR.0b013e3182779193

Stewart, A. D., & Hannan, J. (2000). Total and regional bone density in male runners, cyclists, and controls. *Medicine and Science in Sports and Exercise*, *32*, 1373–1377. doi:10.1097/00005768-200008000-00003

Wang, E., & Hull, M. (1997). A dynamic model of an off-road cyclist. *Journal of Biomechanical Engineering*, *119*, 253. doi:10.1115/1.2796088

Ward, K., Hunt, K., Berg, M., Slawson, D., Vukadinovich, C., McClanahan, B., & Clemens, L. (2004). Reliability and validity of a brief questionnaire to assess calcium intake in female collegiate athletes. *International Journal of Sport Nutrition and Exercise Metabolism*, *14*, 221.

Warner, S. E., Shaw, J. M., & Dalsky, G. P. (2002). Bone mineral density of competitive male mountain and road cyclists. *Bone*, *30*, 281–286. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11792598

Wilks, D. C., Gilliver, S. F., & Rittweger, J. (2009). Forearm and tibial bone measures of distance- and sprint-trained master cyclists. *Medicine and Science in Sports and Exercise*, *41*, 566–73. doi:10.1249/MSS.0b013e31818a0ec8