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Scoping review

Road cycling and bone health: a scoping review

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Abstract:
Introduction: In competitive road cycling, low body mass is a common focus for many athletes. Due to the high energy expenditure and non-weight bearing nature of competitive road cycling, there are associated health risks including relative energy deficiency and low bone mineral density. Untreated, this can lead to an increased susceptibility to fracture. This can be a particular problem in competitive road cycling where the prevalence of falls is high. **Methods:** A scientific literature search on studies investigating relative energy deficiency and bone mineral density in the sport of road cycling was performed. **Results:** Twenty-four studies investigated the relationship between road cycling and relative energy deficiency, bone mineral density, bone structure, calcium and vitamin D, markers for bone metabolism and strength training. Road cyclists were generally found to be at risk of relative energy deficiency and reduced bone mineral density. However, bone strength indices on peripheral quantitative computed tomography were not reduced. There was also conflicting evidence on the effect of consuming calcium and vitamin D on markers for bone metabolism and bone mineral density. Studies supported evidence that the inclusion of strength training can have a positive effect on bone mineral density in road cyclists. **Discussion:** Relative energy deficiency in road cyclists is particularly concerning due to its detrimental impact on bone health and general increased risk of injury. Similarly, low bone mineral density is worrying due to high prevalence of falls and subsequent fracture risk. While it remains to be seen whether calcium and vitamin D supplementation provide adequate bone protection, increased education among competitive road cyclists on the benefits of energy balance and strength training in terms of bone health could be useful and should be advocated by their support team. **Conclusion:** There was evidence of increased risk of relative energy deficiency, low bone mineral density and increased bone resorption in road cyclists. However, there was also evidence that strength and impact training could improve bone health in competitive road cyclists.

Keywords: relative energy deficiency (RED-S), osteoporosis, bone, bone mineral density (BMD), road cycling, cyclist

1. Introduction

Despite the clear overall health benefits associated with engaging in regular road cycling, competitive cycling has been associated with low bone mineral density (BMD) (Abe et al. 2014; Guillaume et al. 2012; Mojock et al. 2015; Nichols & Rauh, 2011; Olmedillas et al. 2011). Bone is dynamic and is constantly remodelled by two counteracting metabolic forces – formation and resorption (Mathis & Caputo, 2018). Bone metabolism is a multifaceted process, including biological and environmental factors and when these factors are imbalanced, negative skeletal adaptions can occur (Baker & Reiser, 2017). Bone is remodelled in response to the strain placed upon it, and strain below a minimum threshold will cause bone resorption (Mcveigh et al. 2015). Weight-bearing activities consistently result in greater BMD than non-weight-bearing activities. Competitive cycling, therefore, with its minimal external loading on areas such as hip, pelvis, and lumbar spine, has consistently been labelled a non-osteogenic sport (Baker & Reiser, 2017).

Mineral deficiencies and dietary restrictions may also exacerbate the issue of low BMD. Competitive cycling and training at elite level requires a high workload over a prolonged period, which may disrupt calcium homeostasis (Baker & Reiser, 2017). Many competitive cyclists are also at risk of relative energy deficiency in sport (RED-S), which has been linked to loss of skeletal mass (Torstveit et al. 2018). This can occur in part due to weight loss practices to maintain a low race weight for competitive advantage (by improving power to weight ratio), and high energy expenditure associated with large volumes of training and racing (Haakonssen et al. 2015). Untreated, low BMD may lead to increased susceptibility to fracture (Mathis & Caputo, 2018). This makes low BMD in cyclists particularly troubling because of the high prevalence of falls and subsequent vulnerability to fracture.

A search of the literature found that cycling does not appear to confer any significant osteogenic benefit, and further research on bone metabolism, bone strength and structure in cyclists has been recommended (Olmedillas et al. 2012). The aim of this scoping review is to summarise the existing available literature regarding bone mass, bone metabolism and energy availability in competitive road cyclists, make recommendations on how this could be applied to current practices, and identify gaps in the research warranting further study.

2. Materials and Methods

A search was carried out using the online database PubMed in October 2021. The search strategy to identify appropriate articles was ("relative energy deficiency" OR "RED-S" OR "osteoporosis" OR "bone" OR "BMD") AND ("road cycling" OR "cyclist"). These results were filtered to include studies published in the last 10 years and written in English. This revealed 152 results. The inclusion criteria were that BMD or RED-S in road cycling had to be the primary area of subject focus in each study. A total of 217 citations were excluded for the following reasons: (a) 71 studies did not include BMD or RED-S or road cycling; (b) 43 studies included road cycling but did not address the impact on BMD or RED-S as the main subject; (c) 14 studies included BMD or RED-S but this was not addressed in the context of the sport of road cycling.

3. Results

Twenty-four studies involving 858 participants were included, from youth to master categories (14 – 71yrs). Amateur to professional level cyclists were involved in the studies, with a variety of comparison groups utilized (sedentary, high impact or weightbearing). (Table 1)

Table 1. Studies

Study	Number of Participants	Gender	Age	
			Range	Mean (SD)
Abe et al. (2014)	27	Male	Master 53-71 Young 20-30	Master 61(6) Young 23(4)
Baker & Reiser (2017)	42	Male Female	18-49	Male 32.9 (9.6) Female 29.4 (6.7)
Corsetti et al. (2015)	9	Male		28.8 (3.6)
Grasso et al. (2013)	9	Male		28.8 (3.6)
Guillaume et al. (2012)	29	Male		26.5 (5.3)
Haakonssen et al. (2015)	32	Female	17-32	24.3 (4.1)
Hoon et al. (2019)	97	Male		32.0 (1.7)
Lane et al. (2019)	108	Male		38.6 (13.8)
Lombardi et al. (2014)	9	Male		26.7 (2.5)
Lombardi et al. (2012)	76	Male Female		
Mathis & Caputo (2018)	40	Male	31-69	42.7 (9.4)
Mathis et al. (2015)	17	Male		42.7 (9.4)
Mcveigh et al. (2015)	30	Male	18-34	Road Cyclists 22.9 (3.4) Mountain bikers 26.0 (5.8) Controls 26.9 (5.5)
Mojock et al. (2015)	28	Male	21-54	
Nichols & Rauh (2011)	37	Male	40-60	Master cyclists 50.7 (4.0) Controls 50.7 (4.1)
Olmedillas et al. (2011)	44	Male		Cyclists 16.9 (1.9) Controls 16.7 (2.1)
Olmedillas et al. (2018)	42	Male	14-20	Cyclists 17.3 (0.9) Controls 18.0 (2.3)
Oosthuyse et al. (2014)	10	Male		29.6 (11.1)
Oosthuyse et al. (2017)	52	Male		Road cyclists 22.9 (3.4) Runners 25.0 (2.7) Mountain bikers 26.0 (5.8) Swimmers 21.8 (2.3) Controls 26.9 (5.5)
Prioreschi et al. (2012)	30		19-59	Vibration group cyclists 44.0 (9.6) Control group cyclists 38.7 (5.7) Sedentary control group 40.8 (9.1)
Sherk et al. (2014)	14	Female	26-41	34.9 (4.8)
Sherk et al. (2017)	51	Male	18-45	Calcium group 35.1 (6.5) Placebo group 36.8 (8.0)
Torstveit et al. (2018)	31	Male	18-50	34.7 (8.1)
Viner et al. (2015)	10	Male Female	29-49	Male 42.0 (7.7) Female 38.4 (10.3)

Each study was independently evaluated and information about the number of participants, level of competition, type of data, and characteristics such as age and gender collected. Results were then assessed and recorded. (Supplementary Table 2).

Relative Energy Deficiency in Sport (RED-S)

Three studies involving 149 participants addressed RED-S, and all found significant risk of low energy availability in cyclists (Lane et al. 2019; Torstveit et al. 2018; Viner et al. 2015). This was thought to be due partly to high energy demands and eating disorders, or disordered eating to maintain a low body weight (Lane et al. 2019). One study also reported that cyclists were highly weight conscious and engaged in a variety of practices to reduce weight, which may be harmful to bone health (Hoon et al. 2019).

Changes in Bone Mineral Density (BMD) on Dual X-ray Absorptiometry (DXA)

Fourteen studies used dual x-ray absorptiometry (DXA) as a means of assessing bone density. Lower BMD was found in the femoral neck, hip, pelvis, and lumbar spine in cyclists compared to controls (Abe et al. 2014; Guillaume et al. 2012; Mojock et al. 2015; Nichols & Rauh, 2011; Olmedillas et al. 2011). Trained cyclists were also more likely to meet criteria for osteopenia or osteoporosis (Mojock et al. 2015; Nichols & Rauh, 2011). Three studies reported evidence that BMD in cyclists reduced with training and competing over 5 months (Mathis et al. 2015), 12 months (Sherk et al. 2014), and 7 years (Nichols & Rauh, 2011) respectively. One study, however, found no change in BMD in cyclists over 6 months (Baker & Reiser, 2017).

Bone Geometry and Structure

Peripheral quantitative computed tomography (pQCT) offers three-dimensional imaging, evaluating bone size, strength, and geometry. Mcveigh et al. (2015) found higher radii strength indices and greater cortical area and thickness in road cyclists compared to controls. However, in a study by Oosthuyse et al. (2017), the radial and tibial indices of road cyclists were not found to be any greater when compared to athletes from other disciplines and controls. These findings support the focus on bone size, strength and mineral density of the femur and lumbar spine in cycling populations.

Calcium and Vitamin D Supplementation

Three studies looked at the effect of calcium and vitamin D intake with conflicting results. Haakonssen et al. (2015) found that eating a calcium rich meal pre-exercise attenuated an exercise-induced rise in markers of bone resorption, but Sherk et al. (2017) found it made no difference. Mathis et al. (2015) also found no difference in BMD loss over a season when taking calcium and vitamin D supplements. Thus, the evidence for supplementing road cyclists with calcium and vitamin D to maintain bone health is limited.

Bone Turnover Markers

Seven studies investigated the impact of road cycling on markers of bone metabolism in serum, sweat and urine samples. Many noted an increase in markers for bone resorption, which could negatively impact bone health (Corsetti et al. 2015; Grasso et al. 2013; Lombardi et al. 2012; Mcveigh et al. 2015; Olmedillas et al. 2018; Oosthuyse et al. 2014). However, Guillaume et al. (2012) found that biochemical markers of bone metabolism and parameters of calcium homeostasis were in the normal range. Oosthuyse et al. (2017) found no significant difference in bone ALP and CTX between road cyclists and controls and athletes from other disciplines. Additionally, in their study on how the Giro d'Italia impacted serum concentrations of calcium and phosphate, Lombardi et al. (2014) concluded that an increase in fibroblast growth factor 23 (FGF23) may be aimed at maintaining calcium and phosphorus homeostasis, yet they did not note any imbalance in bone turnover.

Strength Training

Four studies reported higher bone mineral density associated with self-reported strength training (Mathis & Caputo, 2018; Nichols & Rauh, 2011) and impact exercise (Nichols & Rauh, 2011) and three times per week whole-body vibration training (Prioreschi et al. 2012). One study noted engagement in strength training was highest in international level cyclists. (Hoon etal. 2019) Common reasons for not participating in strength training were time constraints, beliefs that time would be better spent riding, and it wouldn't improve performance or weight gain would decrease cycle performance (Hoon et al. 2019).

4. Discussion

This review found a vulnerability to relative energy deficiency (RED-S) in competitive road cyclists. Importantly within sport, athletes experiencing RED-S are thought to be more likely to have an increased risk of injury and decreased athletic performance (Lane et al. 2019). Within the context of this review, this is especially concerning as RED-S has also been linked to low skeletal bone mass (Torstveit et al. 2018). However, if cyclists can remain in energy balance, bone mass may be better protected (Baker & Reiser, 2017). Additionally, improved bone health can be achieved through engaging in weight-bearing strength activities and potentially supplementing diet with calcium and vitamin D.

In cyclists, low BMD on DXA showed up consistently in studies and this is concerning as it may increase susceptibility to fracture. This is particularly important because fractures appear to be relatively frequent injuries in top-level cyclists and almost all of these are caused by falls (De Bernardo et al. 2012; Haeberle et al. 2018; Rooney et al. 2020). In a study by Rooney et al. (2020), fractures were the second commonest injury and resulted in a high number of days lost to injury, not to mention the long-term impact of these fractures on the riders' morbidity. De Bernardo et al. (2012) also found that 64% of fractures occurred in competition, where group falls are particularly difficult to prevent due to the proximity of riders. Strikingly, an 8-year study on withdrawals from the Tour de France found that 49% were due to fractures, representing the most common reason for withdrawal (Haeberle et al. 2018).

In terms of the impact of road cycling on bone turnover, many of the studies noted an increase in markers of bone resorption, which could potentially negatively impact bone health. However, it is unclear whether this causes a reduction in bone mass. This negative impact of cycling on bone health could potentially be ameliorated using weight-bearing strength exercises as well as foot vibration plates. The greatest barriers to such training, however, were time constraints, negatively impacted body image and the belief that it didn't benefit performance. Thus, when prescribing strength-based activities to road cyclists these barriers must be addressed to promote better adherence to the strength exercise prescription. Indeed, in their review on optimising strength training for endurance performance Rønnestad & Mujika (2013) concluded that strength training can be successfully prescribed to enhance endurance performance in highly trained athletes. Furthermore, no negative effects were reported following the addition of strength training to an endurance training program in their review.

5. Practical Applications.

From this scoping review, road cyclists are at high risk of low bone mineral density, which can present with frequent low trauma fractures. To improve bone health in road cyclists, we would suggest regular monitoring of bone health via a DXA scan (e.g., annually). They should also aim for at least the recommended daily intake of calcium (700-1000mg) and if this is not possible, supplement their diets with 400-600mg of calcium ("Osteoporosis and diet", 2021) and 10 micrograms (400 international units) of vitamin D ("Osteoporosis and diet", 2021; "Vitamin D deficiency in adults - treatment and prevention", 2020).

Additionally, we would encourage the riders to have 2-3 weight-bearing strength training sessions per week, including the use of foot vibration plates. However, compliance needs to be improved by addressing the common barriers which road cyclists report to engaging in strength training. These barriers include time constraints and the false belief that strength training negatively impacts performance (Rønnestad & Mujika, 2013). Further research would therefore be helpful to determine the minimal strength training dose required to affect bone mineral density and the impact of strength training on body composition. Bone health in road cyclists should be addressed through a multi-disciplinary team of nutrition, coaching, strength, and conditioning (specific to road cycling) and sports medicine.

A limitation of this study is that it is a scoping review in one medical database. A systematic review, including further scientific databases and the grey literature, should be undertaken in this area. Studies included also have low numbers of participants, and some are not comparable to competitive road cyclists in age, training time etc. This reflects a lack of relevant data for this cohort, and a prospective study on bone health in elite cyclists may be of benefit to update the research. Additionally, these studies focus on participants currently involved in road cycling. Further research is also recommended to assess the reversibility of bony changes in road cyclists

6. Conclusions

This scoping review has shown that road cyclists are at high risk of having low bone mineral density and therefore, a high risk of fractures. Elite cyclists were found to be prone to relative energy deficiency, either due to high energy expenditure or deliberately reducing food intake as a means of weight control. Bone health in road cyclists can be improved with strength-based and whole-body vibration training activities as well as supplementing the diet with calcium and vitamin D. Further research needs to be conducted into the bone health of road cyclists, highlighting osteopenia and osteoporosis as real medical risks in this cohort of athletes, and investigating real-world strategies to address this.

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Table 2. Results

Reference	Number of participants	Gender	Age Range	Mean Age (SD)	Exercise history	Data collected	Results
Abe et al. (2014)	-14 master cyclists -13 moderately active young men	-Male	-Master 53-71 -Young 20-30	-Master 61 (6) -Young 23 (4)	-Master cyclists - training 4-5 times per week, ~200 miles per week for on average the last 17 years (range 7–38 years) -Moderately active young men - exercising less than twice a week	-DXA	-Lumbar spine BMD - no different between groups -Femoral neck BMD lower in cyclists
Baker and Reiser (2017)	-22 male cyclists -20 female cyclists	-Male -Female	-18-49	-Male 32.9 (9.6) -Female 29.4 (6.7)	-USA Cycling Category 1-4	-Health history -Cycling questionnaire -4-day dietary log -DXA	-No difference in BMD between subgroups pre-season -No significant change in BMD for any group post-season
Corsetti et al. (2015)	-9 cyclists	-Male		-28.8 (3.6)	-Professional cycling team in the 95th Giro d'Italia 2012	-Bone biomarkers	-Reduction in bone turnover rate and depletion of bone matrix

Grasso et al. (2013)	-9 cyclists	-Male		-28.8 (3.6)	-Professional cycling team in the 95th Giro d'Italia 2012	-Bone biomarkers	-Urinary excretion of calcium and phosphorous increased which could mark an increased rate of bone resorption sustained by increase of sclerostin across the race
Guillaume et al. (2012)	-29 cyclists	-Male		-26.5 (5.3)	-Professional	-Questionnaire on calcium intake -DXA -Bone biomarkers	-Lumbar spine BMD lower than controls -Femoral BMD less affected -Biochemical markers of bone turnover and parameters of calcium homeostasis in normal range
Haakonssen et al. (2015)	-32 cyclists	-Female	-17-32	-24.3 (4.1)	-25 Australian National Road Series (NRS) registered cyclists with at least 18 months racing experience -Additional participants - 1 international professional, 1 ultra-endurance mountain biker, 5 National club-level cyclists	-DXA -Bone biomarkers	-Eating a calcium rich pre-exercise meal attenuates the exercise-induced rise in markers of bone resorption PTH and CTX

Hoon et al. (2019)	-97 cyclists	-Male		-32.0 (1.7)	-Highest local club level (A/B grade) or higher. Included local, national, and international level	-Questionnaire	-49% unsatisfied with current bodyweight -79% trying to reduce bodyweight -9% using supplements or medications to lower bodyweight -27% sought health professional advice -Higher proportion of international riders strength training (85%), compared to national (50%) and club (55%)
Lane et al. (2019)	-108 competitive recreationally trained endurance athletes in running, cycling or triathlon	-Male		-38.6 (13.8)	-Training at least 10 hours per week and currently training for a specific endurance event	-Survey of diet and training records	-Relatively high prevalence of being at risk of low energy availability - 47.2% at risk - 19.4% no risk -Cyclists at greater risk than runners or triathletes

Lombardi et al. (2014)	-9 cyclists	-Male		-26.7 (2.5)	-Professional cycling team, competing in the 94th Giro d'Italia 2011	-Bone biomarkers -Dietary calcium and phosphorus -BMI -Net energy expenditure -Power output	-FGF23 increased 50% -Rise in FGF23 may maintain calcium and phosphorus homeostasis
Lombardi et al. (2012)	-61 athletes - Weight bearing (15 male rugby players, 11 male enduro-racers, 8 female basketball players) - High impact (6 male tennis players, 8 female ice skaters) - Non-weight bearing (13 male cyclists) 16 sedentary controls	-Male -Female			- "Elite"	-Bone biomarkers	-Higher sclerostin and bone ALP in females -Sclerostin higher in weight-bearing than in non-weight-bearing disciplines in males -Significant inverse age-related correlation -Applied load increased marker concentrations, testifying a high bone turnover rate -Gender effect evident

Mathis and Caputo, (2018)	-40 cyclists	-Male	-31-69	-42.7 (9.4)	-State, regional, and national competitors (including 1 former Olympian) -Older than 30 years, "trained regularly" and at least 2 years of cycle-specific experience	-Questionnaire -DXA	-Weight training associated with higher BMD of the lumbar spine, total hip, femoral neck, and femoral trochanter
Mathis et al. (2015)	-17 cyclists	-Male		-42.7 (9.4)		-DXA	-Femoral trochanter BMD significantly decreased during 5-month season -No difference in BMD between cyclists who took a calcium and vitamin D supplement and the control group

Mcveigh et al. (2015)	-10 road cyclists -10 mountain bikers -10 sedentary controls	-Male	-18-34	-Road cyclists 22.9 (3.4) -Mountain bikers 26.0 (5.8) -Controls 26.9 (5.5)	-Road cyclists trained for distance road racing -Mountain bikers trained for distance mountain bike events -Sedentary controls did ≤2 hours structured physical activity per week	-Dietary calcium -Global Physical Activity Questionnaire -BMI -DXA -pQCT -Bone biomarkers	-Mountain biker radii significantly stronger, denser, and larger compared to road cyclists and controls -Road cyclists significantly higher strength indices and greater cortical area and thickness than controls at the radial diaphysis -Serum CTX higher in road cyclists than mountain bikers and above the general population age reference range
Mojock et al. (2015)	-28 cyclists	-Male	-21-54		-Riding more than 3 hours per week	-DXA -VO2 max -Training history	-Trained cyclists had lower hip BMD bilaterally -Lumbar scans identified 12 trained and 4 recreational cyclists as osteopenic and 3 trained cyclists as osteoporotic

Nichols and Rauh, (2011)	-19 master cyclists -18 controls	-Male	-40-60	-Master cyclists 50.7 (4.0) -Controls 50.7 (4.1)	-Cyclists - Year-round cycling training consistently for at least 10 hours per week, at least 150 miles per week, for at least 10 years; and competing in United States Cycling Federation (USCF) races for a minimum of 10 years -Controls – Nonathletic but active and matched to cyclists by age and body weight	-Health questionnaire -DXA -Calcium intake	-Lower BMD in cyclists compared to nonathletes at all bone sites -Greater BMD decline in cyclists than controls -If weight training or impact exercise since baseline, significantly less BMD lost at spine and femoral neck -Significantly greater percentage of cyclists than nonathletes met criteria for osteopenia or osteoporosis at baseline -6 of the 19 (31.6%) cyclists with osteopenia at baseline became osteoporotic, compared to 1 (5.6%) of the nonathletes

Olmedillas et al. (2011)	-22 cyclists -22 age matched controls	-Male		-Cyclists 16.9 (1.9) -Controls 16.7 (2.1)	-Cyclists - regular regional competitions, training/competitions for a mean of 10 hours per week for 2-7 years -Controls - recreational sports (rugby, tennis, handball, soccer) 2 hours a week with occasional match at the weekend but none cycled more than 1 hour per week	-Physical activity questionnaire -VO2 max -DXA	-Cyclists had lower BMC and BMD compared with healthy age-matched controls for the whole body, pelvis, femoral neck, and legs -Differences in BMC and BMD between cyclists and controls were higher in adolescents over 17 years old
Olmedillas et al. (2018)	-22 cyclists -20 age matched controls	-Male	-14-20	-Cyclists 17.3 (0.9) -Controls 18.0 (2.3)	-Cyclists - Regular regional competitions and mean training/competition load of 10 hours per week for 2-7 years -Controls - recreational sports for less than 2 hours per week, and occasional matches at the weekend but no one cycled more than 1 hour per week	-Questionnaire -Bone biomarkers	-Cycling during adolescence may be associated with a decrease in bone turnover and may affect bone health later in life

Oosthuyse et al. (2014)	-10 cyclists	-Male		-29.6 (11.1)	-8.3 ± 4.6 years of cycling experience -12.7 ± 6.2 hours cycling training per week	-Sweat calcium excretion during exercise -Bone biomarkers	-Persistent increase in bone resorptive activity following overnight recovery during 4 successive days of prolonged strenuous cycling may be expected to have long-term negative consequences for bone health
Oosthuyse et al. (2017)	-10 road cyclists -9 runners -10 mountain bikers -13 swimmers -10 controls	-Male		-Road cyclists 22.9 (3.4) -Runners 25.0 (2.7) -Mountain bikers 26.0 (5.8) -Swimmers 21.8 (2.3) -Controls 26.9 (5.5)	-Athletes from local sports clubs training a minimum of 5 hours/week for at least 2 years and no other non-sports-specific training -Sedentary controls <2 hours/week of exercise	-Dietary questionnaire -BMI -pQCT -Bone biomarkers	-No difference in tibial indices of road cyclists and mountain bikers compared to controls -No significant difference in serum bone ALP and CTX between road cyclists and other participants

Prioreschi et al. (2012)	-8 road cyclists in the vibrating group -7 road cycling controls -15 sedentary controls		-19-59	-Vibration group cyclists 44.0 (9.6) -Control group cyclists 38.7 (5.7) - Sedentary control group 40.8 (9.1)	-Cyclists – road cycling for at least 5 years and for a minimum of 8 hours per week -Sedentary controls – healthy, exercising for less than 2 hours per week	-DXA -Calcium intake questionnaire - Cardiorespiratory exercise test	-Cyclists who had 10 weeks of whole-body vibration training showed significant increase in hip BMD, control cyclists - no change -Cycling control group significantly lower spine BMD compared to baseline, spine BMD preserved in cycling vibration group
Sherk et al. (2014)	-14 cyclists	-Female	-26-41	-34.9 (4.8)	-At least 1 year of competition history and intent to compete in 10 or more races in the coming year	-DXA -pQTC	-Bone loss at lumbar spine, total hip, and subtrochanteric region of the hip -No significant trabecular or cortical bone changes in the tibia over 12 months of training

Sherk et al. (2017)	-23 cyclists taking a calcium supplement -28 cyclists taking a placebo	-Male	-18-45	-Calcium group 35.1 (6.5) -Placebo group 36.8 (8.0)	-Competed in road cycling races for at least 1 year with plans to participate in at least 10 more races in the next calendar year	-DXA -Bone biomarkers	-Serum calcium decreased in both calcium-ingesting and placebo groups from before to after exercise but there was a greater decrease in the placebo group -Non-significant attenuation of the increase in PTH by calcium supplementation -No effect of calcium on CTX, which increased in both groups
Torstveit et al. (2018)	-31 cyclists, triathletes, and long-distance runners	-Male	-18-50	-34.7 (8.1)	- "Trained" or "well-trained" and at performance levels 3-4 -Training frequency at least 4 sessions/week during the previous year and competing at a regional or national level	-BMI -DXA -VO2 max -Resting metabolic rate -Resting heart rate -Energy status -Serum glucose, cortisol, testosterone and T3	-65% of subjects had suppressed RMR -Male endurance athletes with suppressed RMR, despite similar energy availability and 24-hour energy balance spent more time in severe energy deficit and had larger single-hour energy deficit compared to those with normal RMR

Viner et al. (2015)	-6 male cyclists -4 female cyclists	-Male -Female	-29-49	-Male 42.0 (7.7) -Female 38.4 (10.3)	-USA Cycling Category: Pro, n=2; 1–4, n=8 -Endurance cyclists (5 road, 5 off-road)	-Dietary records -DXA -Three-Factor Eating Questionnaire	-90% low energy availability during at least 1 training period -70% low energy availability across the season -70% identified as restrained eaters who consciously restrict energy intake as a means of weight control -No difference in energy availability between male and female cyclists and road and off-road cyclists