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Sustainability of exercise-induced increases in bone density and skeletal structure

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Abstract

Background: The prevalence of osteoporosis with related fragility fractures has increased during the last decades. As physical activity influences the skeleton in a beneficial way, exercise may hypothetically be used as a prophylactic tool against osteoporosis.
Objective: This review evaluates if exercise-induced skeletal benefits achieved during growth remain in a long-term perspective.
Design: Publications within the field were searched through Medline (PubMed) using the search words: exercise, physical activity, bone mass, bone mineral content (BMC), bone mineral density (BMD) and skeletal structure. We based our inferences on publications with the highest level of evidence, particularly randomised controlled trials RCT.
Results: Benefits in BMD achieved by exercise during growth seem to be eroded at retirement, but benefits in skeletal structure may possibly be retained in a longer perspective. Recreational exercise seems to at least partially maintain exercise-induced skeletal benefits achieved during growth.
Conclusions: Exercise during growth may be followed by long-term beneficial skeletal effects, which could possibly reduce the incidence of fractures. Exercise during adulthood seems to partly preserve these benefits and reduce the age-related bone loss.

As reviewed in an accompanying review (1) and reported in previous publications (2–12), the incidence of fragility fractures has increased during the last half of the 1900's. This is related to an increased prevalence of osteoporosis in society, predominantly due to an increased aging population (12–14). Whether the age specific incidence of osteoporosis has increased is unclear. Today there exist treatment of osteoporosis. Drugs to treat osteoporosis (15) have in randomised controlled trials (RCT) been shown to increase the bone mineral density (BMD) by 5–10% and reduce the fracture risk (16, 17). But other strategies for fracture prevention are also needed, strategies that influence BMD in a beneficial way without side effects and methods that are available for most individuals without high costs.

Epidemiological studies convincingly show that bone mass (BM) or bone mineral content (BMC) or BMD are closely associated with the risk of sustaining a fracture (18). A 10% decrease in BMD, corresponding to one standard deviation (SD), is associated with a doubled fracture risk (18). But, it is also imperative to realise that BMD is a poor predictor of the individual fracture risk, as so many other risk factors influence the risk of suffering a fracture (4, 13, 18–20).

Physical activity during growth is associated with obvious skeletal benefits in both the accrual of bone mineral and gain in bone structure, especially in the late pre- and early peri-pubertal period (21–37). Mechanical strain that includes a high load, a fast load or a load affecting the skeleton in an unusual direction confers the highest anabolic response. The duration of exercise is of less importance, as a short duration of load or a small number of repetitions are enough to achieve the maximal anabolic effect. Thus, high intensity sports like squash, tennis, soccer, ice-hockey, badminton and volleyball are

most effective if the goal is to reach skeletal benefits. But clinically relevant questions remain – do these exercise-induced skeletal benefits remain with residual benefits into old ages, into the ages when the incidence of fragility fractures exponentially increases?

This review evaluates if the well-documented exercise-induced skeletal benefits achieved during growth remain in a long-term perspective.

Method
The search for papers to be included in the review was done in Medline (PubMed). The search words: exercise, physical activity, bone mass, bone mineral content, bone mineral density, BMC, BMD and skeletal structure were used. Included in the review were only papers or abstracts published in the English language. No restriction on the time period studied was used, and studies in adults or those dealing with the long-term effects of exercise were included. From the relevant papers included in the Medline search, a further search was undertaken by choosing the connection 'related manuscripts'. Preferably, prospective, randomised controlled trials (RCT) were then included in this overview, as this is the highest ranked study design in evidence-based systems. If no RCT was found, the next level of evidence in the evidence-based hierarchy was scrutinised, i.e. non-randomised controlled studies, then retrospective and prospective observation cohort studies, and finally case-control studies. As an enormous amount of publications exists within this field and with these study designs, we predominantly included those with the largest sample size and the longest follow-up period. But, it must be emphasised that this is not a systematic review with pre-specified inclusion criteria or a meta-analysis. Neither did we intend to include all papers published within this topic. Instead, we tried to interpret the enormous amount of data within the field in order to summarize the current concept within this topic.

Results and discussion

Are exercise-induced benefits in bone mineral density achieved during growth eroded by time?
Animal studies indicate a decline in exercise-induced benefits over time. One trial including 50 young rats, randomised to 8 or 12 weeks of training and then 4 weeks of detraining revealed that femoral wet weight, bone volume, cross-sectional area and cortical area all increased with the training regime, but that all benefits were lost with the 4 weeks of detraining (38). Another rat trial (39) supports that the effects of detraining should be followed for a long period, since all benefits in BMC were eventually lost with detraining (40). Bone turnover studies in humans do not oppose this view. Trials report that there are discrepancies in bone turnover when

comparing active soccer players with retired soccer players. Another study reports that 2 weeks of detraining are followed by increased bone resorption and a decreaed bone formation.

However, there are reports that both support and oppose that exercise-induced BMD benefits are maintained after cessation of exercise (43–54). One cross-sectional trial in tennis players infers that the arm to arm discrepancy in BMC remains undiminished after detraining. This suggests that benefits in BMC are maintained with reduced activity level (45). The prospective reports that support the maintenance of BMC or BMD benefits with cessation of exercise all have a questionable study design that could confound the conclusions. Some studies do not include more than 12 retired athletes (45), others include retired athletes still on a higher than average activity level, all studies have followed the former athletes only in a short period of retirement, and in one study that suggests BMD benefits to be retained with retirement, there is actually some regions with a higher BMD loss than in controls (46, 51–54). Therefore, we must be aware that these trials can include a type II error; the former athletes could still be on an activity level that influences the BMD, and the period of retirement could be too short to capture any increased age-related loss in BMD.

When looking at prospective data in a longer perspective of retirements, the results are less promising. One trial, at baseline including middle-aged runners, reported that 5 years later the loss in spine BMD was 13% in those who stopped running in comparison with 4% in those who continued to run (55). Similar data was reported in a short-term study, evaluating unilateral leg presses four times a week for 12 months in 12 women aged 19–27 years. The training period in this cohort was followed by a non-significant increase in BMD, but 3 months of detraining was followed by a return to the pre-training BMD level (56). Another similar report in 29 premenopausal women with regular training for 12 months supports this view. The programme was followed by a significant increase in BMD compared to 22 controls, but that all these benefits were lost with 12 months of detraining (57). There are now also two larger prospective controlled studies published that follow former athletes for 5–8 years into retirement (43, 44). The first study included 97 male ice-hockey and soccer players and 49 controls (43), and the second study included 66 female soccer players and 64 controls (44). Both reported that the athletes had a 1–1.5 SD higher BMD at baseline than controls, but after 4–5 years of retirement, the remaining exercise-induced benefits in BMD were approximately halved. These two studies revealed that the loss in BMD following retirement was greater than the age related loss in controls.

When evaluating the effect of retirement over decades, we have to rely on cross-sectional data. One trial including

22 active and 128 former active male soccer players and 138 controls indicated that the former athletes still had higher BMD during the first two decades after retirement, but lower than the active soccer players (35). The diminution in leg BMD was 0.33% per year in the former soccer players compared to a loss of 0.21% per year in the controls (Fig. 1). After 5 years, the leg BMD was 10% higher than age-matched controls in the former players, after 16 years 5% higher but no longer higher in players retired for 42 years (Fig. 1). In spite of the more extensive loss with retirement, the leg BMD was 6% higher in the former soccer players, now over 70 years, than in controls, a non-significant difference when comparing unadjusted, but significant when comparing the values adjusted for differences in body composition (35). No benefits were seen in the hip, spine or any other skeletal region. The only variables that correlated with BMD in this study was age and current level of activity, not past level of activity. Also cross-sectional data in female former soccer players support this view. Twenty-five female former soccer players, aged 40 years and retired for 10 years, still had higher BMD than controls, however less than during their

active career (58). These female athletes were unfortunately not followed in a long time perspective, so any residual benefits after age 65 could not be evaluated in this report. Also male former weight lifters had higher total body BMD after cessation from active career, by 8% when they were 35–49 years old, by 6% at 50–64 year, but not higher than controls when they were 65–79 years (47–49). Similar data have been reported in retired professional male and female ballet dancers both in Australia (59) and Sweden (50), as well as in retired Australian gymnasts (34).

Are exercise-induced benefits in bone structure eroded by time?

Even if all benefits in BMD seem to be lost with detraining, there is a possibility that the structural changes, induced by exercise during growth, could be retained. The enlargement in bone size in the dominant upper extremity in former tennis players was maintained with cessation of exercise (45). In this study, 12 male former tennis players retired for 1–3 years were evaluated by peripheral computed tomography (pQCT). Humeral shaft arm to arm differences in total cross-sectional area of bone was 13% higher, cortical area 23%, bone strength index 24%, principle moments of inertia 41% and cortical wall thickness 20% higher compared to controls (45). The marrow cavity was also larger in the dominant arm suggesting that a greater endocortical expansion during activity or a higher endocortical resorption after retirement had occurred. The observations fit with the hypothesis that exercise produces enlargement of bone size that is permanent, but that the increased mineralisation through an endocortical apposition may be lost with retirement. Further, short-term studies from the same research groups support the view that cessation of exercise is associated with remaining benefits in bone structure (51–54). The same view was supported in a RCT, including 239 children aged 3–5 years (60). In this study, 12 months of physical activity including the large muscle groups was followed by both periosteal and endosteal expansion and these differences compared to controls remained with 12 months of detraining. This is probably of biological importance, as placing the cortical shell further away from the centre of the tubular bone will increase the bone strength by the fourth power of the radius (61).

But evaluation of benefits in a longer perspective has to rely on cross-sectional data. Bone size was larger in 90 male former soccer players and weight lifters aged 50–92 years and retired from their exercise career 3–65 years ago, in comparison with 77 sedentary age- and gender-matched controls, both at the femoral neck and the lumbar spine (62). Furthermore, in this study there were also remaining benefits in the old former athletes evaluated by quantitative ultrasound (QUS). This is of special interest as QUS usually estimates not only the
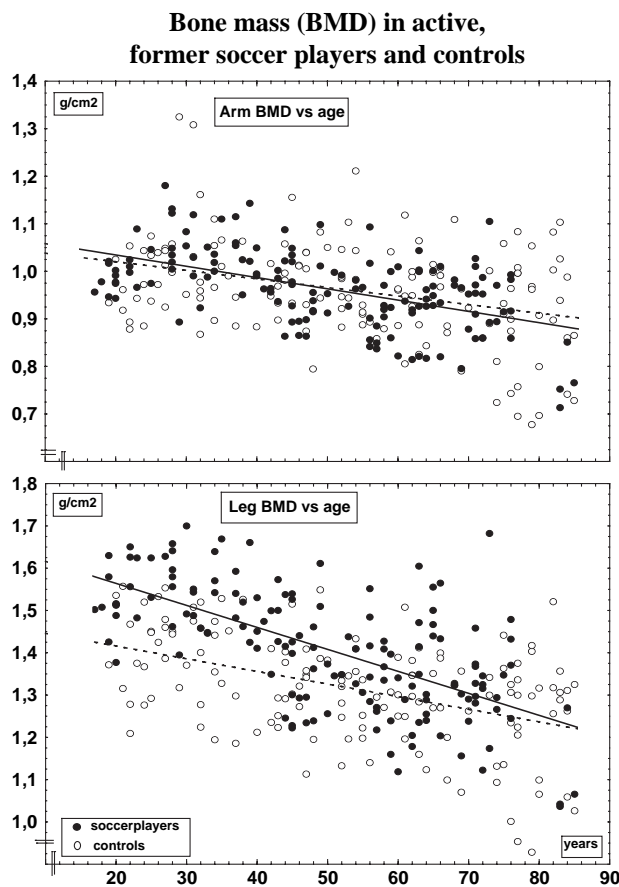

Bone mass (BMD) in active, former soccer players and controls

Fig. 1. Bone mass (BMD, g/cm²) of the legs and arms in active, former soccer players and controls versus age. Adapted from Karlsson et al. (35).

quantity of bone mineral, but also the quality of the skeletal architecture (63), a trait not captured by the DXA technique. These latter data indicate that exercise-induced structural skeletal changes, not captured by the DXA method, are possibly preserved in former athletes into old age and might then reduce the fragility fracture risk. However, further prospective cohort studies and long-term evaluated cross-sectional trials are needed to support such inferences.

Conclusions

Physical activity on a level that most individuals can perform increases the accrual of BMD during growth. Moderate activity seems to reduce the BMD loss in adulthood. The Achilles' heel of exercise is its cessation. Exercise-induced skeletal benefits in BMD achieved during growth seem to be lost with cessation of exercise, whereas exercise-induced structural benefits in the skeleton may be retained even with reduced activity level. Physically activity on a recreational level seems to retain some of the skeletal benefits achieved during growth.

Recommendations

Based on current scientific knowledge, we should recommend a continual physically active lifestyle during adulthood as one prevention strategy to reduce the high incidence of osteoporosis-related fractures.

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Conflict of interest

No conflicts of interest exist.

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