The Association of Sport Participation on Lower Limb Bone Architecture in Children and Adolescents: A Scoping Review and Preliminary Meta-Analysis

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INTRODUCTION: Skeletal loading from physical activity during the circumpubertal phase is paramount to accruing bone mass. Bone quality (i.e., architecture) is another component of bone assessment that has gained interest in recent years due to the accessibility of high-resolution imaging modalities which allows the direct measure of these parameters. Greater magnitudes of bone architecture parameters such as cortical thickness and trabecular density increase estimates of bone strength and therefore suggest better bone quality. Participating in sports can increase the frequency and intensity of mechanical loading and is believed to further improve bone mass and quality. The purpose of this review was to synthesize the current literature to examine the association between sport participation and bone architecture in youth athletes.

METHODS: A scoping review and meta-analysis (MA) was conducted in literature published 1980-2024. Articles were included if they included athletes ≤19 years old and examined a lower limb bone via high-resolution imaging. Articles were excluded if they included adults (>19 years old) or animals, did not include athletes, used low-resolution imaging modalities only, or imaged the upper limbs only. Article screening and extraction of bone architecture parameters from all included studies was completed by two independent reviewers. MA was conducted using a random effects model to assess the difference between athletes and controls. For studies that had multiple sport cohorts, the means and standard deviations for each sport group were averaged together to generate a single athletes group mean and standard deviation for the study. If study stratified athletes and controls by sex, then means and standard deviations for each sex were averaged together to generate a single value for that group. Between study heterogeneity was assessed with I-squared (I^2) statistics with an $I^2 \geq 50\%$ representing substantial heterogeneity. To assess the effect of sex, when applicable, random effects models were conducted for each outcome comparing athletes and controls by sex separately. To assess the effect of loading potential, sports were subdivided into two groups of weight-bearing (WB) and non-weight bearing (NWB). WB included any sport where the athletes not only fully supported their own weight but could exceed that amount from different movements (e.g., soccer, track-and-field, gymnastics, etc.). NWB included any sport where the individual did not bear the full weight of their body in the low extremity (e.g., swimming, water polo, cycling, etc.). Random effects models were conducted on WB and NWB sports separately for each applicable site and parameter. All MA were conducted if there was a minimum of two studies for a specific parameter and anatomical site. Results included number of studies included in the analysis (K), total sample size (N), standardized mean difference (SMD), 95% confidence intervals (95% CI), p value, and I^2.

RESULTS SECTION: 5503 studies were initially identified with 21 duplicates; 4567 were deemed irrelevant; 915 articles were included in the full text screen with 900 excluded. 15 studies were included in this review (13 cross-sectional; 1 longitudinal; 1 RCT). Sports included gymnastics (6/15), track-and-field (4/15), soccer (3/15), swimming (2/15), cycling (2/15), triathlon (1/15), water polo (1/15), and 1 study grouped into 3 levels of participation frequency termed 'high-power', 'low-power', and 'no-power'. Inclusion criteria varied across studies with some focusing on time per week, while others included a minimum prior participation duration (e.g., 2 years). At minimum all studies required the athletes to participate in an organized sport at the regional level, however some studies required competitors from the national or elite level of their respective sport. 13/15 studies included 'non-athlete' controls with inclusion criteria varying across studies ranging from <2 hours of physical activity per week to no limit on physical activity as long as they didn't participate in organized sports. Athletes and controls were 13.7±3.3 and 13.5±3.6 years old on average across studies. 3/15 studies had males only, 4/15 had females only, and 8/15 included both sexes. MRI (3/15) and pQCT (12/15) was used to image the femur (2/15) and tibia (14/15). The femur was imaged at the mid-point and femoral neck. The tibia was imaged at 66% of tibial length, 38%, 14%, 4%, and 10 mm from the distal metaphysis. When considering each study individually, NWB sport athletes had greater femoral bone mineral content and total bone volume than controls. Likewise, NWB sport athletes had greater total bone mineral content, total cross-sectional area and polar strength-strain index than controls at the proximal tibia diaphysis (66% site). Conversely, NWB sport athletes had less cortical thickness and bone strength index at the distal tibial diaphysis (38% site) compared to controls. Female athletes of WB sports had greater tibial cortical bone volume and bone mineral content (tibial and femoral neck) than female controls. The MA revealed no differences between athletes or controls at the distal tibial metaphysis (4% site), distal tibia diaphysis (38% site) or proximal tibia diaphysis (66% site). When stratified by sex, athletes had greater bone strength index (males: k=2, n= 267, p=0.008, I^2=64.3, SMD=0.656, 95% CI 0.168 – 1.143 mg^2/mm^4; females: k=2, n=262, p=0.013, I^2=67.2, SMD=0.685, 95% CI 0.146 – 1.224 mg^2/mm^4) and trabecular cross-sectional area (males: k=2, n=157, p=0.028, I^2=51.0, SMD=0.569, 95% CI 0.062 – 1.077 mm^2; females: k=2, n=112, p=0.048, I^2=0.0, SMD=0.387, 95% CI 0.004 – 0.770 mm^2) than controls at the distal tibia metaphysis (4% site). There were no significant effects when stratified by loading potential.

DISCUSSION: WB sports demonstrated positive effects on the tibia and femoral neck in females whereas there were no differences observed between groups for males. Conversely, NWB sports had positive effects on the femur and proximal tibia. Qualitatively assessing studies suggest positive sport and anatomical-site specific associations, but due to most studies being cross-sectional it is unclear if sport participation is the primary factor or if individuals gravitate towards sports that favor their body type. When data was pooled together there were no differences unless stratified by sex, demonstrating the important role of sex hormones in bone metabolism. The conflicting results from independent assessment vs MA may be due to the heterogeneity of inclusion criteria for both groups. In particular, the varying degrees of participation duration confounds associations as each group will likely have a different exposure magnitude. Likewise, when pooled together, the analyzed sample includes pre-adolescent and adolescent athletes, eliminating any control of pubertal status which further influences bone metabolism. More longitudinal studies using high-resolution imaging modalities and stricter inclusion criteria are needed to delineate the contribution of sport participation versus general physical activity to bone quality.

SIGNIFICANCE/CLINICAL RELEVANCE: Preliminary evidence would suggest that organized sport participation is particularly beneficial to bone quality in females and there may be anatomical specific adaptations dependent on sport. However, it is difficult to discern if sport participation is the primary driver of these associations over general physical activity due to the limitations of study designs.