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Adaptive Skeletal Responses to Mechanical Loading during Adolescence

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Abstract

Adolescence, defined as the period between puberty and maturity, provides a 'window of opportunity' for positive skeletal adaptations to mechanical loading unlike any other period in life. Age-related bone loss highlights the importance of accumulating sufficient bone mass during formative years. Adolescents who regularly engage in weight-bearing mechanical loading appear advantaged in site-specific markers of bone mass. The positive influence of physical activity on bone mineral accrual during growth has been extensively studied; however, few studies have examined skeletal responses to mechanical loading during adolescence. Weight-bearing physical activity, particularly high-impact sports such as gymnastics, is recognised as being more osteogenic than weight-supported activities. Unilateral loading activities such as tennis or squash provide a direct comparison of skeletal response without sampling bias or genetic confounding. Intervention and longitudinal studies show evidence of positive skeletal adaptations; however, sustainability of skeletal advantages remains unclear. Limitations inherent with single-plane dual x-ray absorptiometry technology are well recognised. The integration of densitometric data with structural responses to mechanical loading using 3-dimensional imaging technologies such as peripheral quantitative computed tomography and magnetic resonance imaging appears vital to enhancing our understanding of adolescent musculoskeletal health.

The framework of the human skeleton provides protection of internal organs, support against gravity, a lever system enabling movement and a reserve of ions for the maintenance of serum homeostasis. Active adolescents require a skeletal system with a composition (material properties) and organisation (structural properties) to accommodate functional demands of intense physical activity within a lightweight design facilitating energy-saving locomotion.[1]

Peak bone mass reflects the maximal lifetime amount of bone mineral accrued in individual bones and the whole skeleton.[2] Peak bone mass value is a consequence of net accrual of bone during childhood and the balance between accrual and resorption in adulthood.[3] Theoretically, because bone loss occurs with aging, people who acquire maximal bone mass in their early years should be at a reduced risk of skeletal fragility and fracture in later life. Agreement on the age at which peak bone mass is achieved remains illusive and site specific.[2,4-8]

Genetics determine the basic morphology of the skeleton, but final bone mass and architecture are modulated by adaptive mechanisms sensitive to mechanical loading.[9] Pioneer research in loading conducted by Wolff (1882) was the first to document changes in bone mass that accompany different mechanical loadings. Internal architecture and external structure alter as a consequence of primary stimuli from mechanical loading.

1. Material Properties of Bone

Deformation is the process that occurs when a force is applied to bone. The process is coupled with the generation of internal resistance to counter the applied force. The internal reaction, known as stress, is equal in magnitude but opposite in direction to the applied force.[1] Strain, however, is defined as the deformation of material relative to its own dimensions and is calculated by dividing change in bone dimension by original bone dimension. Induced mechanical strain is the key intermediate process occurring between mechanical loading and bone adaptation. Increased loading produces minute changes in the surface curvature of bone and generates a strain gradient signal that activates bone cell response.[7] Strains, however, must be above or below threshold levels for bone to have an adaptive response.[10]

Signals inducing mechanical strain may be amplified by interstitial fluid flow through canalicular channels. The contents of the bone fluid compartment relocate from surfaces of greater concavity to surfaces of greater convexity when bone is deformed in bending.[11] Dynamic loading and relaxation of bone create shear stresses on cells that allow an adaptive response. Rates of fluid flow through the bone fluid compartment are proportional to the sheer stresses generated on bone cells. Higher strain rates produce greater fluid velocity and an increase in sheer stress.[12] The application of a compressive end-load to the ulnae of growing male rats for 10 min/day across 2 weeks was examined in three treatment groups.[13] The groups received: static loading at 8.5N, static loading at 17N, or dynamic loading at 17N. Dynamic loading proportionally increased osteogenesis significantly on both periosteal and endocortical surfaces. The result supports the concept that fluid flow mediates the mechanical signal.

Bone reacts differently when it is stretched (tensile strain) or compressed (compressive strain). Curved or bent bone exposes the concave surface on the bottom of the femoral neck to compressive stresses and tensile stresses on the top of the femoral neck, as shown in figure 1.[11] A neutral axis exists at some point between the two surfaces and represents the point at which the strains are zero. Theoretically, the load placed on the periosteal surface will be greater than loads placed on the endocortical surface because of the distance from the neutral axis.

Mechanical loading increases bone apposition at the surfaces in a state of net formation. During childhood, net formation occurs on the periosteal surface and net resorption on the endocortical surface.[14] Late in puberty, however, the predominant effect of mechanical loading is endocortical apposition, particularly in women.[15] Increased diameter of bone distributes material further from the neutral axis and improves resistance to bending or torsional loads.[1]

Bone mass is increased by mechanical loading through the application of resistance or increased weight-bearing activity. Mechanical loads that generate high-load magnitudes are more likely to pro-

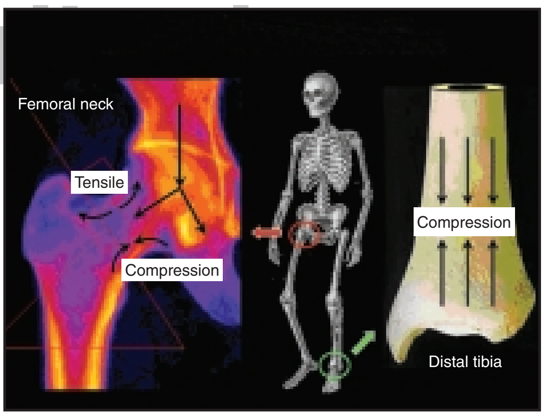

Fig. 1. Example of different loading conditions at the femoral neck (tensile and compression) and distal tibia (axial compression).

duce an osteotrophic effect than low-intensity loads.[16-18]

2. Cross-Sectional Studies

Cross-sectional studies allow comparisons of different physical activity patterns such as sporting and non-sporting populations and, as such, provide a worthwhile indication of the benefits of activity. Activities in which bodyweight is carried create forces on skeletal sites sufficient to stimulate gains in bone mass. The current review of cross-sectional studies will focus on high impact loading sports, comparative studies of gymnasts and runners, weight-loaded sports, weight-loaded sports versus weight-supported sports and unilateral loading sports such as tennis and squash.

2.1 High-Impact Loading

Gymnastics is characterised by high-impact loads through repeated jumps and body contact with hard surfaces. In order to quantify impact loading in gymnastics, ground reaction forces of common gymnastic manoeuvres were measured. Assessment of ground reaction forces from male gymnastics training sessions revealed 102–217 impacts on upper and lower extremities with peak magnitudes of 3.6- to 10.4-times bodyweight.[19] The effect of high-impact loading forces on bone mineral density (BMD) in upper limbs of late adolescent/young adult female gymnasts was recently described.[20] Vaulting studies show forces on the upper extremity of between 1.13- and 1.57-times bodyweight and 3.1-times bodyweight on uneven bars. Compared with controls, gymnasts had significantly higher lumbar spine, total right proximal, left proximal femur and total body BMD. Higher bone mineral content (BMC) was also found in gymnasts compared with controls at all sites. A comparison of adolescent athletes from high-impact sports (running, gymnastics, tumbling and dance) with elite swimmers found greater femoral neck BMD in athletes from the high-impact sports than the swimmers.[21] The findings of higher densities at the proximal femur suggest the femur may experience greater mechanical loading during high-impact activities than other skeletal sites. Similar advantages in BMD at the femoral neck were evident in adolescent male weightlifters who displayed greater femoral neck and lumbar spine BMD compared with age-matched controls.[22] Furthermore, an investigation of the influence of two different types of high-impact weight-bearing activity (rope skipping and soccer) in BMD in late-adolescent females resulted in significantly higher BMD at most loaded sites in both high-activity groups compared with controls.[23]

2.2 Gymnasts and Runners

Peri-pubertal Caucasian female gymnasts, runners and controls were studied over 12 months to determine the effect of high-impact loading on the growing skeleton. The 12-month follow-up data were adjusted for age, height, Tanner stage, BMD at baseline and increases in height and weight. Gymnasts showed greater increases in femoral neck and trochanter BMD than runners or controls. Lumbar spine BMD did not differ between groups.[24] Similarly, higher femoral neck BMD was observed in late adolescent female gymnasts, compared with runners and controls.[25] In addition, runners showed lower total body BMD values compared with gymnasts. Collectively, the studies highlight the superior site-specific BMD profile at the femoral neck of gymnasts compared with other sport participants and less active controls.

2.3 Weight-Loaded Sports

The BMD of early adolescents involved in sports producing significant impact loading on the skeleton was compared with age-matched controls from non-weight-bearing sports.[21] Eight men and nine women were recruited from impact-loading sports such as running, gymnastics, tumbling and dance and were matched for race, sex, stage of puberty and bodyweight with competitive swimmers. Athletes from impact-loading sports had greater femoral neck BMD and a tendency for greater lumbar spine BMD than swimmers. Non-sporting weight-bearing activity appears to have a similar impact on the bone mineral of pre- and early-pubertal populations. Seventy-eight female pre- and early-pubertal ballet dancers were compared with 52 age-matched controls. Mean weekly hours of formal dance training were 4.6 hours/week and all dancers had attended dance classes on average for the past 4.3 years. Participation in dance training was associated with 4.5% greater BMD and 7% greater areal BMD at the femoral neck. Differences could not be explained by maturity, size or body composition differences between groups.[26]

BMD of late-adolescent women participating in the weight-loaded sport of competitive rope-skipping training was compared with female soccer players and nonathletic healthy controls.[23] The skipping group had significantly higher BMD at total body, lumbar spine, trochanter and the diaphyses of femur and tibia than controls. Soccer players also had greater BMD at proximal femur, total femur and the diaphyses of femur and tibia than controls. No differences were found between the two high-activity groups except for a higher radial BMD in the skipping group than the soccer group. Activities incorporating significant impact loading on the skeleton appear to result in greater gains in site-specific BMD compared with participants exposed to reduced impact loading.

2.4 Weight-Loaded versus Weight-Supported Sports

The influence of different mechanical loading patterns on BMD in elite adolescent female cyclists, runners, swimmers, triathletes and controls has been investigated. Differences in BMD between weight-bearing (running), non-weight-bearing (swimming and cycling) sports, and a sport that incorporates both types of loading conditions (triathlon) were compared. Runners had greater total body, lumbar spine, femoral neck and leg BMD than controls. Runners also had higher total body, femoral neck and leg BMD than swimmers and greater leg BMD than cyclists.[27] Results suggest that athletes engaged in weight-loaded activities appear advantaged in total body and regional BMD compared with athletes involved in weight-supported activities.

2.5 Unilateral Loading

Comparisons of bone mineral properties of sporting people with non-sporting people are problematic because of the plethora of factors in addition to mechanical loading that contribute to bone biology and responses to stimuli. These factors include genetic background, nutrition, self-selection, compliance, activity intensity even within the same training group, hormonal activity, previous injuries and body composition. Confounding, however, can be partly overcome by intra-individual comparisons. To avoid genetic confounding, bilateral intra-individual variations in BMC and BMD for dominant and nondominant limbs in children aged 8–16 years were examined.[28] Greater BMC and BMD in the dominant arm compared with the nondominant arm were attributed to greater habitual loading. In a similar study, site-specific effects of loading were examined in pre-, peri- and post-pubertal female tennis players. Humeral BMC was greater in the loaded arms of pre-pubertal players as a result of greater periosteal apposition. Results suggest loading further supports the contention that structural changes are enhanced by adolescent growth.[29]

Post-pubertal differences in BMC of the playing and non-playing arms of young adult female national level tennis and squash players have also been examined.[30] Selection criteria included ≥5 years of participation and mean starting age of playing careers was 16 years. Compared with controls, the dominant to nondominant side difference in BMC was significantly greater in players at the proximal humerus, humeral shaft, radial shaft and distal radius. A similar examination of impact loading on bone mass and size in young adult female tennis and squash players was undertaken.[31] Players were divided into two groups according to the age at which they commenced tennis or squash training to examine possible differences in bone structure and density. At the humeral shaft, the loaded arm contained greater BMC with the greatest side-to-side difference detected in young starters compared with later starters and controls. Thus, it appears the adaptive skeletal responses to unilateral loading was greatest during the adolescent years.

Results from cross-sectional studies provide compelling evidence to suggest physical activity produces gains in bone mass. Weight-bearing activities in particular, appear more osteogenic than weight-supported activities. Similarly, athletes exposed to unilateral loading reveal greater gains in site-specific bone mineral compared with unloaded regions. Cross-sectional studies, however, only highlight possible differences between heterogeneous groups. Intervention studies enable researchers to control participant exposure to stimuli, thereby producing more robust research outcomes.

3. Intervention Studies

Exercise intervention studies address the hypothesis that exercise during childhood and adolescence increases bone density. Studies recruiting children from distinct maturity stages seek to determine the phase of growth during which bone responds optimally to physical loading.[32] Research has progressed from weight-bearing generic activities, higher intensity circuit-based loading, resistance and plyometric training, to highly prescriptive acute bouts of jumping activities. A number of intervention studies have been conducted in pre-pubertal boys,[33,34] girls[35] and both sexes[36-38] with a consensus that the effectiveness of additional weight-bearing activity to bone may be attenuated prior to puberty.

The effect of weight-bearing, high-impact exercise on BMC in two distinct groups of pubertal girls was investigated. Twenty-five pre-menarcheal and 39 post-menarcheal girls completed a step-aerobic programme twice a week for 9 months. Thirty-three pre-menarcheal and 29 post-menarcheal girls served as controls. In pre-menarcheal girls, BMC increased more in the intervention group than controls at lumbar spine and femoral neck. Post-menarcheal girls showed no significant post-training differences in BMC. The authors concluded the 9-month exercise intervention programme produced large additional bone gain in exercising pre-menarcheal girls but not exercising post-menarcheal girls.[39]

The consequence of site-specific loading through progressive resistance training on BMC and BMD was examined in post-menarcheal adolescent girls. Four sets of 13 exercises were performed three times per week for 26 weeks using hydraulic resistance machines. Despite a trend towards a transient increase in lumbar spine bone mineral during the first 13 weeks, there were no significant changes in total body or lumbar spine bone mineral between intervention and control groups.[2]

Using a similar maturational cohort, the effects of plyometric jump training on bone mass was investigated in post-menarcheal adolescent girls aged 13–15 years. Twenty-five girls completed plyometric training for approximately 30–45 minutes per session, three times per week for 9 months.[40] Progressive resistance training and simple plyometrics were performed for the first 3 months of the programme. In the final 6 months of the programme, advanced plyometrics including jumps, depth jumps, bounding and hopping were introduced. Twenty-eight controls were matched by age and months past menarche. Intervention girls failed to show greater changes in BMC than controls despite trends in BMC improvements across skeletal sites. The authors suggest the post-pubertal skeleton is not as responsive to exercise training as the pre-pubertal skeleton.

Difficulties in comparing the responsiveness of the skeleton to structured physical loading during growth are compounded by timing and onset of maturational events and difficulties in quantifying that equal loading has been imposed within and where appropriate between groups. Intervention studies involving children and adolescents have predominantly focused on females and have examined osteogenic responses across the spectrum of maturational stages. Results suggest changes in bone mass and structure appear particularly responsive to physical loading in the pre- and peri-pubertal years. The prescription of exercise to maximise osteogenic responses in children and adolescents, however, remains equivocal. The majority of school-based intervention studies involve 10–20 min/day of weight-bearing impact activities with three or more sessions per week. The prescription of 3 days of exercise per week may potentially advance oestogenic responses in children and adolescents; however, longitudinal studies are required to ascertain the sustainability of gains in bone mineral.

4. Longitudinal Studies

The long-term effects of mechanical loading on bone mineral accretion in child and adolescent populations are not fully understood. Cross-sectional studies generally report a positive association between mechanical loading and bone mineral accrual throughout childhood and adolescence; however, longitudinal consequences of the sustainability of exercise-induced bone gains are relatively unknown.

Longitudinal studies that span the entire pubertal period must control for considerable maturational differences in children and adolescents of the same chronological age. A 6-year study that annually evaluated the relationship between physical activity and bone mineral accrual in children passing through adolescence, used peak bone mineral content velocity (PBMCV) as a common maturational landmark to compare participants.[41] Children in the highest activity quartile for physical activity accrued more bone across the 6-year period than inactive children. Highly active children also demonstrated greater total body BMC 1 year after PBMCV compared with least active children. At regional sites, active children had 18% greater BMC at the lumbar spine compared with the least active group. Results provide more credible evidence to suggest physical activity positively influences bone mineral accrual in the growing skeleton.

A similar study examined the effect of physical activity on bone mineral accretion in boys and girls aged 9–16 years.[42] Highly active boys and girls between ages 9–13 years demonstrated greater femoral neck BMC and BMD than less active controls. Three years of further high and low activity did not augment differences in bone size and mass in either girls or boys. Baseline data of BMC/BMD and physical activity, however, were gained at age 13 years using a cross-sectional study design, raising concerns about sampling bias. Furthermore, physical activity levels from 9–13 years were evaluated retrospectively by questionnaire in order to determine annual activity level. Despite methodological concerns, results appear to challenge the belief that physical activity may advance gains in bone mineral in pre-pubertal years, but provide no additional gains in the peri-pubertal period.

Conflicting results were gained from a 3-year longitudinal study that compared changes in total body and regional BMC/BMD in pre- and peri-pubertal female gymnasts with non-exercising controls.[43] Annual measurements over a 3-year period showed gymnasts displayed greater areal BMD than controls at all sites except for the total body. Gains in BMD at the lumbar spine, femoral neck, trochanter, Ward's triangle, and distal and mid radius were achieved by gymnasts despite maturational progression. Results highlight the benefits of weight-bearing exercise on bone mass acquisition throughout the pre- and peri-pubertal period.

In contrast to the pre-pubertal years, a 3-year longitudinal study examined the effect of physical activity on the accumulation of bone mass in post-pubertal male athletes and controls.[44] At baseline, athletes from badminton and ice hockey displayed greater total body, dominant and non-dominant humeral and femoral neck BMD than age-matched controls. At the 3-year follow-up, athletes had greater BMD at all sites. Bone mass differences between athletes and controls were greatest at sites exposed to high mechanical loading, such as the femoral neck and dominant humerus. Although results suggest physical activity positively influences bone mineral accrual in healthy adolescent males after puberty, selection bias from comparing cross-sectional data at 16 and 19 years of age cannot be discounted.

A similar study compared changes in bone mass in male and female post-pubertal track and field athletes with non-athletic controls over a 12-month period.[45] At baseline, male and female athletes displayed greater bone mass at loaded sites compared with control groups; however, a genetic predisposition to higher bone mass in athletes warrants acknowledgement. Modest but significant increases were found in total body BMC and femur BMD in athletes and controls during the 12-month study. Athletes also displayed greater increases in bone density at the lumbar spine when compared with controls. Baseline results indicate an association between greater bone mass and participation in track and field training. Longitudinal data after 12 months of athletic training suggest additional gains in bone mass can be achieved in the post-pubertal period.

Longitudinal analysis of data gained from intervention studies minimises the influence of selection bias inherent in cross-sectional studies with well matched controls at baseline. A 20-month follow-up study assessed the effect of a 9-month jumping intervention on bone gain in growing girls.[46] Immediately after the jumping intervention, trainees displayed 3.6% greater BMC at the lumbar spine than controls. At the 20-month follow-up, BMC gains at the lumbar spine had increased to 4.9% in trainees when compared with controls. No other between-group differences were found in BMC at the 20-month follow-up. Despite continued participation in step-aerobic training by one-third of the trainees between the 9-month intervention and 20-month follow-up, previous participation in high impact training appears to produce residual bone gain in growing girls.

Changes in bone mass from training and bone loss from detraining were found in a 2-year longitudinal study involving post-pubertal female gymnasts.[47] In the initial 12-month period, total body, hip and lumbar spine BMD increased during the 8-month training season, but BMD values decreased in the 4-month off-season. The same pattern of bone gain and loss occurred throughout the second 12-month period. The results suggest a transient adaptive response to training in adolescents. However, the lack of a control group masked the conclusion that gains in BMD were related to gymnastics training rather than normal growth-related bone accrual. Furthermore, reproductive endocrine status was not established despite the inclusion of athletes with menstrual irregularities, calcium intake was not recorded, and a small sample size of eight participants limits the generalisability of results.

Selection bias and other confounding factors inherent in cross-sectional studies potentially obscure our understanding of skeletal adaptations to exercise. Longitudinal studies, therefore, provide a greater opportunity to examine the influence of mechanical loading on bone mineral accretion over time. Few longitudinal studies, however, encompass the entire pubertal period due to time, long-term compliance demands and financial restrictions. Differences in study design, athletic groups, maturational stages and densitometry further preclude the comparison of existing longitudinal studies of bone mass accrual in child and adolescent populations.

5. New Technology

Traditional densitometric measures of bone mineral status, such as BMC, using dual x-ray absorptiometry (DXA), are poor independent indicators of bone strength.[48] Numerous studies[31,49,50] have reported improvements in bone strength due to altered spatial distribution of bone mineral without simultaneous gains in bone mass. However, limitations inherent with single-plane DXA technology and assumptions of bone shape, particularly in growing children, are well recognised.[51] Densitometry-based techniques for assessing bone structural parameters have subsequently been established. Hip structural analysis software integrates geometric information and absorptiometry data by applying engineering beam theory to provide a measure of bone-bending strength. Cross-sectional studies involving prepubertal female gymnasts[52] and intervention studies involving pre- and early-pubertal females[53] highlight the adaptive geometric response of the proximal femur to mechanical loading.

Superior assessment of bone strength, however, requires 3-dimensional imaging technology. Animal research has shown that bone strength index (BSI) from the integration of peripheral quantitative computed tomography (pQCT) and DXA data revealed a greater correlation between BSI and actual fracture load than BMD alone.[54] Recently, cortical volumetric BMD and cross-sectional moment of inertia (CSMI) obtained from non-ionising magnetic resonance imaging (MRI) were combined with DXA-derived BMC to provide a useful, non-invasive measure of *in vivo* bone strength.[27] The 3-dimensional geometric capability of MRI complements densitometric measures of BMC and more accurately assess the material and structural properties of bone strength than DXA technology alone. Three studies[15,27,29] have combined MRI with DXA-derived data to examine bone strength in children and adolescents. Loaded versus non-loaded humeral bone strength in pre-, peri- and post-pubertal female tennis players revealed a proportional increase in periosteal apposition and endocortical resorption versus the contralateral limb only in pre-pubertal athletes.[29] Bone strength in adolescent female athletes engaged in either weight-bearing or non-weight bearing sports has also been examined at the mid femur using a combination of MRI and DXA.[27] Results showed female adolescent athletes involved in weight-loaded sport (running) had greater BSI at the mid femur than athletes engaged in weight-supported sports (swimming and cycling) and non-active controls. Adolescent female middle-distance runners have also displayed greater bone strength at the distal tibia compared with non-athletic, female controls.[15] Compared with controls, female athletes showed superior distal tibial BSI due to a greater accumulation of bone material (volumetric cortical BMD) and a more optimal distribution of bone (CSMI) about the neutral axis. Integration of densitometric measures of bone mineral with structural assessment of bone is vital to enhancing our understanding of adaptive responses to mechanical loading during adolescence.

6. Conclusion

Mechanical loading from physical activity appears a vital osteogenic stimulator of bone mineral. Few studies, however, have accurately quantified loading in weight-bearing and weight-supported activities. Furthermore, the principle number of loading cycles required to achieve sustainable skeletal outcomes has not been determined. Nevertheless, active adolescents have achieved regional and whole-body gains in bone mineral from large mechanical loads that exceed pre-set strain thresholds. Adolescents engaged in high-impact, weight-bearing activities such as gymnastics, appear more likely to exceed strain thresholds than adolescents involved in weight-supported activities such as swimming. Despite equivocal findings, the adaptive responsiveness of bone to mechanical loading appears heightened during the early pubertal/premenarcheal period. The sustainability of residual bone gains in the post-pubertal period remains unclear and further emphasises the need for continued participation in physical activity throughout adulthood. The integration of densitometric data with structural responses to mechanical loading using 3-dimensional imaging technologies appears vital to enhancing our understanding of adolescent musculoskeletal health.

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