Public Health England

Royal Osteoporosis Society

Better bone health for everybody

Muscle and bone strengthening activities for children and young people (5 to 18 years)

A rapid evidence review

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Contents

Executive summary

Poor musculoskeletal (MSK) health is one of the greatest health burdens nationally. It often has its origins in childhood and adolescent physical development (for example 90% of bone density is achieved by the age of 18/20 years). The UK Chief Medical Officers' (CMOs) physical activity guidelines emphasise the need for regular muscle and bone strengthening activities for children and young people but lacks detail on what activities most effectively promote bone and muscular health outcomes in children and young people.

This review adds depth to the guidelines using the most recent evidence. It presents a summary of the specific physical activities and age ranges to promote muscular health and bone health outcomes in children and young people.

Although the relationship between activities and bone / muscle health is a physiological and mechanistic one, there are areas of consideration for equalities that need to be explored, particularly between sexes and for disabled people.

Based on the evidence included within this rapid review, the following conclusions have been drawn:

Weight-bearing physical activities (including weight-bearing sports participation) are effective at stimulating bone development. Evidence was found in support of football, jumping, martial arts and small-sided team games, with the strongest and most consistent evidence found for gymnastics. However, other high intensity weight-bearing activities, with similar characteristics to those activities listed, may confer similar benefits.

The volume of weight-bearing physical activity is important, independent of intensity. Highlighting the importance of regular intermittent activity throughout the day, not just focussed on sport/leisure activity.

Moderate to vigorous intensity weight-bearing physical activity is an effective method of inducing increases in bone mineral density and bone strength, as well as structural improvements in the bones. Although more intense intermittent activity likely produces better bone parameters.

Different approaches to, and types of, interventions may be needed to promote muscular strength and bone heath depending on the age and sex of the child. In terms of developing muscular strength, high impact small-sided games and circuit training were effective for children and traditional and plyometric resistance training in adolescents. However, the period around puberty (when maximal growth occurs) may be the most effective time to intervene to most effectively develop bone health, suggesting the period of 9 to 16 years of age being of greatest importance.

Gaps exist within the evidence base which currently limit the ability to make firm conclusions about the benefits of specific type, duration and intensity of physical activity on bone health and muscular health for this age group. Improvements in research design, exposures used, population groups studied, measurement techniques employed and reporting of protocols would help to strengthen the evidence base.

List of abbreviations

aBMD	Areal bone mineral density
BMC	Bone mineral content
BMD	Bone mineral density
BMI	Body mass index
CMO	Chief Medical Officer
cQUS	Calcaneal quantitative ultrasound
CT	Computed tomography
DXA	Dual-energy X-ray absorptiometry
HSA	Hip structure analysis
LST	Lean soft tissue
MSK	Musculoskeletal
MVPA	Moderate to vigorous physical activity
PHV	Peak height velocity
pQCT	Peripheral quantitative computed tomography
RCT	Randomised controlled trial
SI	Stiffness index
SPA	Single photon absorbency
TBS	Trabecular bone score
vBMD	Volumetric bone mineral density
VPA	Vigorous physical activity

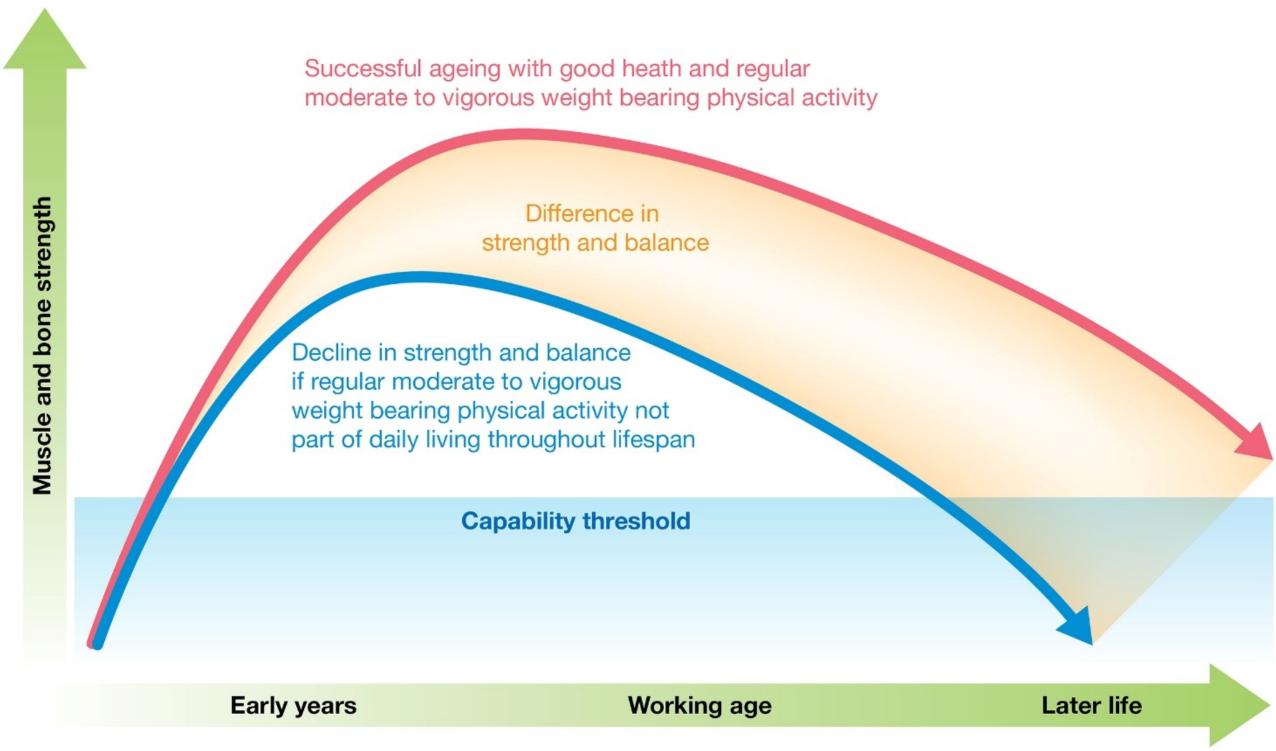
Introduction

Poor musculoskeletal (MSK) health is one of the greatest causes of contemporary ill health in our population[1]. One in 6 of the adult population suffer from a long term MSK condition [2]. MSK issues are the greatest cause of work sickness absence and a primary cause of disability and loss of independence during adulthood [3]. Contrary to popular perception, poor MSK health is not just about ageing, but often has its origins in childhood and adolescent physical development. Physical activity during childhood and adolescence is critical for developing good lifelong MSK health and the associated health and wellbeing benefits [4].

Modifiable health behaviours, such as participating in physical activity, can have a major impact on the development of muscles and bones throughout life [5]. Muscle force is generated during physical activity, and muscle contractions to meet a resistance exert high loads on the skeleton. The ‘mechanostat’ theory describes that bones adapt their strength to the loads applied to them [6]. Muscle as a mediator transfers forces generated during muscle contractions, to bone, thus, muscle and bone should be considered together to better understand the influence of physical activity on bone strength.

As a child grows, bone is constantly developing, being formed and reshaped to keep its function on an ongoing basis. In the process of normal growth, much more bone is made than removed, allowing the skeleton to grow in size and density. As a result, up to 90% of peak bone mass is acquired in girls by age 18 and in boys by age 20, making childhood the absolute best time to invest in bone health through appropriate physical activity and nutrition [7]. This is particularly significant given that physical activity in childhood leads to benefits in bone density and bone strength in adulthood, protecting individuals from low bone density, illnesses and loss of physical function during later life [5]. Muscle and bone health are underpinning components of physical activity. Each contributes independently to overall health and functional ability and can offer lifelong benefits. Evidence from observational studies suggest that muscle strength, bone strength, and balance ability increase in childhood and peak in early adulthood, eventually followed by a decline (see Figure 1) [10].

Figure 1. Physical activity for muscle and bone strength across the life course (Adapted with permission from Skelton and Mavroedi (2018) [11])



Ensuring children and young people undertake sufficient strengthening activities is essential for ensuring they achieve their physical capability, allowing them to participate in physical aspects of life and remain physically disability-free and independent for as long as possible. It therefore needs to be a critical part of how we develop individuals in settings such as schools; for example, educating children about their importance within the health education curriculum [12] and providing opportunities for children to engage in appropriate activities as part of daily activity [13].

At a population level, good MSK health is critical for achieving societal goals, such the Government's Ageing Grand Challenge [14], which aims to increase healthy, independent years of life and enable people to remain independent for longer and stay connected to others to counter loneliness.

Purpose and rationale

The UK Chief Medical Officers' (CMOs) guidelines for physical activity outline evidence-based, age-group specific recommendations for physical activity for good health [4]. However mainstream planning and delivery of physical activity typically focusses on activities to promote cardiovascular health, with the muscle and bone strengthening and balance activities elements largely considered for specific populations and outcomes (for example older adults and falls prevention).

While the CMOs' guidelines consider the health benefits of a range of types of physical activity, there is a lack of detail on physical activity to promote muscular fitness in children and young people. Further work is needed to supplement the current CMOs' guidelines for children and young people to reach consensus on the opportunities to influence physical activity to ensure good lifetime bone and muscular health.

The Royal Osteoporosis Society and Public Health England commissioned this review of the evidence base in relation to children and young people's physical activity for good MSK health and development.

The purpose of this review is to summarise the evidence and identify gaps within the research to inform and facilitate recommendations for action and evidence-based tools to promote muscular and bone health in children and young people.

Method

A 'rapid evidence review' approach was used to conduct the evidence review. Rapid evidence reviews aim to revise and speed up the processes and methods used in systematic reviews without compromising the trustworthiness of the final product. This is done by using a structured and rigorous search, and by employing a quality assessment of the identified evidence [15]. Whilst the evidence searches and search strategy aimed to be as comprehensive as possible within the timescale (April to June 2020), the rapid review was not a full systematic review of all related literature. A rapid evidence review approach was purposefully chosen to build on the knowledge base established from recent large-scale systematic reviews of evidence, completed as part of national and global physical activity guideline development processes, and ensure relevance to the wider population.

The overarching aim was to review the evidence for muscle and bone strengthening physical activities to promote muscular health and bone health outcomes for children and young people and answer the following questions:

What types of physical activities (including specific exercises / training and non-exercise activities), and at what intensities/frequencies, are effective in developing a) bone health outcomes in children and young people and b) muscular health outcomes in children and young people?

What are the health benefits of muscle strengthening and bone strengthening activities in children and young people? This should include the impact on mortality risk, physical health, peak bone mass, obesity, quality of life, self-esteem, academic performance and mental wellbeing.

Are there particular age groups within the 5-18 years age band where muscle and bone strengthening activities have the greatest impact on muscle and bone health outcomes and potential for mitigating previous inactivity?

What are the gaps in the current evidence base which should be addressed through further research?

Data sources

Data sources included:

- electronic bibliographic databases – Embase, Medline, TRIP Database, Web of Science
- systematic reviews via – Cochrane library, EPPI Centre knowledge library

- websites – National Institute of Clinical Health and Care Excellence library portal
- search engines – Google scholar

Search strategy

Depending on the limits of the interface with sources, a Boolean search strategy was applied using the operators AND OR NOT in combination with the following keywords, index headings and free text. Truncation techniques using asterisks and wildcard techniques using question marks were employed when free text searching.

Population:

Child, schoolchild, teen, adolescent, youth, young people, young person, boy, girl, paediatric

Intervention:

Bone strengthening, muscle strengthening, MBSA, MBSE, physical activity, plyometric, exercise, weight-bearing, weight-loading, resistance training, training, skipping, jumping, gymnastics, muscle development, muscle loading

Outcome:

Bone health, skeletal health, bone density, bone mineral density, bone mass, muscle strength, muscle mass, muscle power, muscle fitness, musculoskeletal, MSK, osteogenic, bone geometry, muscle development, muscular strength, muscular power, muscle endurance, musculoskeletal fitness, muscle function, bone development, bone structure, bone strength, peak bone mass, mortality, physical health, health benefits, mental wellbeing, quality of life, self-esteem, obesity, academic performance

Additionally, reference lists of key relevant primary research, systematic reviews and meta-analyses and grey literature were examined to identify further studies. Citation searches of key relevant articles were undertaken.

Searches were limited to English between 2017 to 2020, in order to build on the knowledge base established from recent reviews of evidence completed as part of national and global physical activity guideline development processes and ensure relevance to the wider population. However, the searches were also supplemented with key studies as advised by the expert group.

Study selection

It is worth noting that the questions that the review was attempting to answer were unique and therefore limitations of the review must be acknowledged. However, all forms of empirical evidence were included which had come from published, peer-reviewed research. Studies which included an athlete population were excluded due to the public health focus of this review and the limited representativeness of this group.

The evidence sought was (in order of preference):

- systematic reviews (with or without meta-analysis)
- randomised controlled trials (RCTs) published in the period since the literature search was undertaken for the systematic review/meta-analysis were also included to provide the most up-to-date evidence
- other experimental controlled trials
- longitudinal studies
- cross-sectional studies

Quality of evidence

In undertaking this review, consideration was given to quality of the reviewed studies in terms of a combination of their position within the hierarchy of evidence and: the strength of the association, consistency, specificity, temporal sequence, biological gradient, biologic rationale, coherence, experimental evidence, and analogous evidence.

Findings

A detailed summary of the findings by type of evidence and research question, is provided in the Appendix. However, a summary of the evidence related to each of the review questions is presented below. Unless specifically stated, the evidence presented is relevant to both sexes.

What types of physical activities (including specific exercises/training and non-exercise activities), and at what intensities/frequencies, are effective in developing bone health outcomes in children?

Two systematic reviews and meta-analyses, 5 systematic reviews, 2 RCTs, 8 longitudinal studies, one narrative systematic review and 8 cross-sectional studies were identified relating to this question. The studies reviewed provided agreement that weight-bearing physical activities (including sports participation) have a bone forming (osteogenic) effect, with the strongest and most consistent evidence found for gymnastics and football (soccer). While the data did not point to a specific dose of physical activity that was needed to produce these benefits, there was a trend towards high intensity and more frequent weight-bearing activity producing better bone parameters in children.

Type of physical activity

Nogueira et al [16] reported that short bouts of high-intensity weight-bearing activity can positively affect growing bone in children and young people (5-17 years), and in some cases also impact on lean and fat tissue. Within their systematic review and meta-analysis, trials that combined jumping activities with some other weight-bearing moderate-to-vigorous physical activity (MVPA) resulted in the greatest fat and lean mass changes; whereas the trials that were limited to jumping activities were more likely to report positive results for bone mass, but not for other body composition parameters. Support for jumping as an bone growth (osteogenic) activity also came from Gómez-Bruton et al's [17] systematic review, which found that drop jumping interventions during childhood and adolescence improved bone health parameters such as bone mineral content (BMC), bone mineral density (BMD) and bone structure. Moreover, these effects seemed to be maintained over time.

Three longitudinal studies provided support for the positive effect of weight-bearing sports participation on bone outcomes. Ward et al [18] found mean estimated differences in bone mass, between different trajectories of sports participation, in boys were larger and more consistent across anatomical sites compared to girls. Boys and girls who were consistent sports participators had greater leg BMC than those who dropped out.

The study's findings suggest that there may also be skeletal benefits (whole body BMC) for boys who only started sport in the adolescent period ~14 years of age, even if they have not previously participated. Similarly, former male interscholastic sport participants and female interscholastic power sport participants (members of basketball, cheerleading, football, gymnastics, soccer and/or volleyball teams for at least 2 seasons) were found to have stronger bones than their peers even when adjusting for current physical activity and muscle power [19]. One longitudinal study reported areal BMDin the legs to be higher among adolescents engaged in weight-bearing sports (basketball, tennis, gymnastics, judo, kung fu, karate) than in swimmers [20]. Furthermore, the study identified that changes in lean soft tissue were the most relevant determinant of areal BMD accrual. Independently of fat mass, changes in lean soft tissue explained >54% of the variance observed in bone accrual in the legs. This suggests that the main factor linking these variables is not the presence of weight-bearing activities, but the higher muscle activity generated by the sport practice itself.

One narrative systematic review reported significant benefits of weight-bearing non-elite sports on calcaneal quantitative ultrasound outcomes. High-impact weight-bearing sports, such as soccer playing and gymnastics or dancing, were associated with the greatest benefits for bone health; although swimmers and cyclists were not at any apparent bone advantage and had similar bone health as controls [21]. It is plausible that the swimmers and cyclists may have had favourable muscle strength, and lean soft tissue, as a result of their participation in their respective sports. Finally, one cross-sectional study found favourable BMD outcomes (5-9% higher compared to untrained participants) for adolescent girls who participated in 1.5 hours of sports training (volleyball, basketball, handball) twice a week for 6 months [22].

Three studies specifically examined the effects of soccer on bone health. Lozano-Berges et al's [23] systematic review found that soccer practice during childhood provides positive effects on BMC and BMD compared to sedentary behaviour and other sports (such as tennis, weightlifting or swimming). Soccer players presented higher BMC and BMD in most weight-bearing sites such as whole body, lumber spine, hip and legs. Favourable outcomes were also supported by one cross-sectional study which reported that male adolescent footballers exhibited higher bone density, geometry, and stiffness compared with swimmers, cyclists and controls. Although swimmers and cyclists had higher bone outcomes compared with controls, these differences were not significant [24].

Support was found for gymnastics as an osteogenic activity for children both independently, and in comparison, to other activities. Krahenbüh et al's systematic review [25] found gymnastics, soccer, tennis and capoeira (a martial art that combines elements of dance, acrobatics, and music) to have more favourable outcomes compared to the absence of physical activity. Swimming was inferior not only to other sports but also control groups. A consistent finding was that all studies examining gymnastics found more favourable effects on BMD and BMC compared to non-active groups.

Burt et al's systematic review [26] found that male gymnasts (both recreational and elite) had better bone health outcomes (architecture and strength) compared with controls. Elite and recreational level gymnasts (ages ranged from 4.73 years to 17 years with mean age of 10.2 years) had higher total bone content at the radius, greater total and trabecular bone density at the radius, greater total and trabecular bone density at the radius and tibia, larger bone size at the hip and radius, a thicker radial cortex, and higher estimates of bone strength at the hip and radius. Although not conclusive, there was evidence for male gymnasts to have higher bone density and BMC, larger muscles and bones, and greater estimates of bone strength compared with controls.

Similar support for gymnastics was reported in another systematic review which concluded that gymnasts present higher bone mineral values in comparison with untrained controls. The osteogenic effect of gymnastics has a positive influence on bone mineral accrual and overcomes the possible negative influence of excessive athletic activity that may cause negative energy balance and low body fat mass which are associated with lower bone accrual [27].

One longitudinal study examining the impact of artistic gymnastics on female adolescents' (10-16 years) bone outcomes reported that gymnasts, after a 12-month follow-up, demonstrated a higher BMD in the Ward's triangle and whole femur than the controls, as well as an improvement in femur density. In addition, the gymnasts had significant bone accrual (after 12 months) in the upper limbs, lower limbs, and whole body [28].

Two studies looked at the effects for a variety of martial arts activities. A Barbeta et al's systematic review [29] found significantly better bone outcomes for children and young people participating in taekwondo, judo, karate, kung fu, kyokushinkai and boxing. Moreover, one cross-sectional study showed a greater increase in BMD within a school-based martial arts group (judo, jiu-jitsu, karate, taekwondo, boxing and muay thai) compared to those who only undertook usual physical education [30].

Some support is given for the utility of specific school-based interventions to impact on bone health outcomes, either delivered on school site as an extra-curricular programme or within a specific unit of physical education classes. For example, one RCT found that small-sided games and circuit strength training (3 x 40 mins a week for 10 months) improved bone mineralisation (whole body aBMD and leg BMC) [31].

Dose of physical activity

Evidence for the potential possible existence of a threshold of activity for improvements in BMC and BMD was provided by a Michalopoulou et al cross-sectional study [32]. It reported positive associations between volume of physical activity of both cortical and trabecular vBMD and BMC independent of body mass index (BMI), chronological age, and bone age (an indicator of the skeletal and biological maturity of an individual). These findings suggest that a high volume of habitual physical activity (independent of activity characteristics) is related to a continuous osteogenic response during preadolescence.

A Rowlands et al longitudinal study [33] identified variation in bone health across the activity volume and intensity distribution of an individual's activity profile. It found high intensity being key for aBMD and BMC and higher volumes of lower intensity weight-bearing activity potentially beneficial for hip structural geometry, even if weight-bearing VPA was absent or low. Independent associations with the intensity gradient confirmed the importance of higher intensity weight-bearing physical activity for optimal BMC and aBMD. Further, additive associations of volume and intensity suggested that increasing weight-bearing physical activity of any intensity could also be advantageous for hip aBMD and total body BMC. For spine aBMD, weight-bearing VPA was key in males but no associations were evident in females. This study adds to the evidence that there may be site specific benefits of weight-bearing physical activities which vary by intensity.

One systematic review reported that the most effective interventions included short (10- to 12-minute) sessions of jumping exercises, executed 2 to 3 times per week [16]. Similarly, a Gómez-Bruton et al systematic review [17] suggested that 10 minutes of (drop) jumping twice a week may be enough to improve BMC among children and adolescents. One cross-sectional study found that overall physical activity also had significant relationships with whole body and femoral neck BMC and BMD in adolescent boys [34].

Longitudinal and cross-sectional data identified weight-bearing VPA as an effective method of inducing increases in BMD and bone strength, as well as structural improvements in the bones of children. Metcalf et al's study [35] reported an accumulative impact of weight-bearing VPA on bone strength outcomes throughout adolescence and into emerging adulthood. On average, accumulating 5 minutes per day more weight-bearing VPA was associated with up to 3% greater bone structural outcomes by age 19 in boys and up to 5.1% greater bone structural outcomes in girls. Bielemann et al's longitudinal study [36] found that VPA was more strongly related to aBMD than moderate physical activity in both sexes. Finally, Marin-Puyalto et al's cross-sectional study reported that weight-bearing VPA (in continuous periods of at least 5 minutes) presented the strongest relation with bone mineral parameters; being the only intensity with statistically significant relationships with whole body and lumbar spine BMC values and the highest correlation coefficients with femoral neck BMC and BMD [34].

Moderate-to-vigorous weight-bearing physical activity was also identified as a positive independent predictor of bone strength in one longitudinal study, with findings showing a significant positive association between habitual MVPA with bone strength at the distal radius [37]. In addition, Yamakita et al's cross-sectional study reported that those in the highest tertile of MVPA (approximately > 77 minutes per day) showed significantly higher bone stiffness index compared with the groups with < 77 minutes per day in boys. Although no significant association was found in girls, there were positive dose–response trends across MVPA levels for bone stiffness index in both boys and girls [38]. This study corroborates previous evidence for a dose-response relationship from Gracia-Marco et al who reported that in order to guarantee optimal bone health, it was found that more than 78 minutes/day of MVPA was associated with increased BMD at the femoral neck, more than 19 minutes/day of VPA with increased BMC at the hip and more than 28 and 32 minutes/day of VPA with increased BMD at the intertrochanter and femoral neck [39].

What types of physical activities (including specific exercises/training and non-exercise activities), and at what intensities/frequencies, are effective in developing muscle health outcomes, in children?

The evidence base relating to muscular health outcomes is less developed and fewer studies were identified from the literature search. One systematic review and meta-analysis, 2 RCTs and 3 cross-sectional studies were reviewed relating to this question.

Cox et al's systematic review and meta-analysis [40] examining muscular fitness outcomes in adolescent boys revealed that school-based interventions targeting muscular fitness demonstrated a small to medium effect. Traditional and plyometric methods of resistance training, such as weight machines and free weights, appear to be the most effective form of physical activity delivery in adolescent boys. Exposure to traditional resistance training may allow for preparation towards the transition into a popular form of physical activity conducted by adults. The literature suggests that muscular fitness interventions lasting at least 8–12 weeks are most effective in adolescent populations; although authors acknowledge that intervention duration may not have been long enough in over a quarter of studies to evoke an efficacious response[40].

Support for other school-based muscular fitness interventions was demonstrated by 2 RCTs. Larsen et al's [31] study showed that a school-based intervention, with small-sided ball games and circuit strength training, improved jump performance and postural balance over a 10-month period in school children aged 8 to 10 years. The study's findings suggest that high-impact physical education sessions can be used to promote MSK health in young children.

Liao et al's study [41] reported that a movement orientated functional strength training programme (in comparison with a traditional strength training programme) may be more effective on improvements of movement quality, muscular strength, flexibility, and power in adolescent girls. Interestingly, the evidence reviewed for this question suggests that different approaches and types of muscular fitness interventions may be needed to be effective for adolescent girls compared to boys.

One cross-sectional study provided support for the use of resistance training in male adolescents. Marta et al [42] reported more favourable training induced gains in muscular power as a result of resistance training programme (45 mins of medicine ball throws, jumps onto a box, plyometric jumps, and sets of 30 to 40m speed runs, twice a week for 8 weeks) compared to suspension training (a novel and relatively new form of exercise training that uses instability to help train strength). Of the other cross-sectional studies included in the review, one reported significant improvements in both the flexor and extensor trunk muscles for a sample of high school students following a Pilates training programme (two 55 minute sessions per week for 6 weeks) [43]. The other examined unilateral leg press training of the dominant or nondominant leg on opposing and same side (contralateral and ipsilateral) strength and balance measures. The study reported that both dominant and nondominant leg press training (3 times a week for 8 weeks) significantly increased both opposing and same side lower body strength and power in a sample of adolescent boys [44].

Table 1 provides a summary of the strength of the association between each type of physical activity and bone health and muscular health outcomes.

Table 1. Summary of the strength of the association between each type of physical activity and bone health and muscular health outcomes

Type of sport or activity	Improvement in bone health outcomes	Improvement in muscle health outcomes
Soccer [17,19,21–23]	★★	?
Jumping [14,15]	★★	★
Swimming [19,21,22,43]	◯	?
Gymnastics [17,19,23–26,43]	★★★	?
Tennis (and racket sports) [18,21,23]	★	?
Martial arts [18,23,27,28]	★★	?
Boxing [27,28]	★	?
Circuit strength and resistance training [38–40,42]	★	★★
Weight-bearing sport/ Small-sided games [16,17,19,29]	★★	?
Basketball [17,18]	★	?
Volleyball [17]	★	?
Handball [17]	★	?
Cheerleading/ dancing [17,19]	★	?
Cycling [19,22]	◯	?
Pilates [41]	?	★

Effect: ★★★ Strong ★★ Medium ★ Low ◯ None ? Not known

What are the health benefits of muscle strengthening and bone strengthening activities in children and young people?

One systematic review and meta-analysis, 2 systematic reviews and 2 cross-sectional studies were identified relating to this question.

Historically, whilst much research has been published relating to this specific question, a limited number of studies were found for the period of interest. Those which were included examined both physiological (bone and lean and fat tissue) and psychological outcomes (psychological stress, psychological wellbeing and mental health).

The meta-analysis revealed beneficial effects of school-based, bone-targeted exercise for bone and fat, but not for lean mass [16]. This included favourable effects on whole body, femoral neck and lumbar spine BMC. Lean mass observations were equivocal with considerable variation in lean mass outcomes between trials. The authors concluded that considerable study heterogeneity may have obscured effects on lean mass. However, the effects observed for bone and fat support the pursuit of brief, jumping-focused interventions to reduce fat, as well as enhance MSK tissue in school age children.

One systematic review which examined the association of physical activity with health outcomes, specifically in younger children, found strong evidence demonstrating that higher amounts of physical activity are associated with more favourable indicators of bone health (BMC and cortical bone thickness) in children 3 to 6 years [45]. However, the data did not point to a specific dose or type of activity that was needed to produce these benefits.

Specker et al's [46] systematic review sought to explore whether physical activity in childhood consistently increased BMC, bone area or aBMD. Children assigned to exercise interventions had significantly greater increases in BMC and aBMD but not bone area, than children assigned to control groups. The overall mean difference between the percent change in BMC in the intervention and control groups was 0.9% for total body (95% CI, 0.3–1.3; $p = 0.003$); 1.5% for femoral neck (95% CI, 0.5–2.5; $p = 0.003$); and 1.7% for spine (95% CI, 0.4–3.1; $p = 0.01$). Benefit of exercise was limited to children who were prepubertal with no differences among children who were pubertal.

Two cross-sectional studies examined the association of muscular fitness and psychological outcomes. Janssen et al [47] reported that muscular fitness was not relevant for mental health after no independent association between muscular fitness and mental health (wellbeing and internalising problems) was found in a sample of older adolescents (16 years). Conversely, Rodriguez-Ayllon et al [48] reported that muscular strength was negatively associated with psychological distress (that is stress and negative affect) and positively associated with psychological well-being (that is optimism and self-esteem). Overweight/obese children with higher muscular strength showed lower levels of stress and of negative affect, and higher levels of optimism and self-esteem. Specifically, absolute upper-body muscular strength was negatively associated with stress and absolute upper-body and lower-body muscular strength were inversely associated with negative affect. It may be possible that the overweight/obese population is more sensitive to the psychological effects of physical activity which may account for the differences between the 2 studies.

Are there any particular groups within the 5-18 age range where muscle and bone strengthening activities have the highest impact on muscle and bone strength and potential for mitigating previous inactivity?

One systematic review, 3 longitudinal and 2 cross-sectional studies were identified relating to this question.

Bone mineral contents accumulate relatively slowly throughout childhood [49]. Indeed one study found no evidence for an association between parental reported physical activity on child BMD in a sample of 5 year olds, although strong evidence was found for an association between body composition and child BMD [50].

Previous research, not included within this review, indicated that bone health outcomes due to physical activity are related to maturity level and sex [51], and that changes in BMD during adolescence in particular are sensitive to weight-bearing physical activity [52].

The potential physiological adaptations of the skeletal system indicate that the prepubertal period might be better for bone adaptations from physical activity and exercise compared to the adolescent period [5]. Elhakeem et al's prospective cohort study [53] found that over a 15 year-period, the greatest gains in BMD for both boys and girls were observed between the year before and 2 years after peak height velocity (an accurate and precise marker of puberty timing that allows direct comparisons of this association between boys and girls). Older chronological age at puberty was associated with persistently lower BMD despite this group accruing faster subsequent gains. The magnitude of these gains was greatest between ages 14 and 16 years in both boys and girls. However, it should be noted that these gains reflected changes as a result of normal growth, as opposed to physical activity per se which was not measured.

One systematic review examining whether exercise influences paediatric bone reported that whilst exercise interventions during childhood led to 0.6 to 1.7% greater annual increase in bone accrual, the benefits of exercise were limited to children who were prepubertal [46].

Further evidence in support of this finding is provided from longitudinal studies. Ubago-Guisado et al found that while osteogenic sports participants (footballers) had better bone health compared to non-osteogenic sports participants (swimming and cycling), both groups showed a linear increase in all bone outcomes between 2 years before and 2 years after peak height velocity. Furthermore, the differences in bone outcomes between groups increased with biological age [54].

More favourable bone health outcomes have also been reported between peripubertal soccer players when compared to their post pubertal peers. Higher BMD and BMC in peripubertal girls, and BMC in peripubertal boys, were found at the femoral neck in a cross-sectional study of a sample of soccer players [55]. Whilst this study suggested that playing soccer during the peripubertal stage could be an effective activity to achieve optimal bone mass values, another longitudinal study reported on the benefits of VPA to promote osteogenesis in adolescents. Bielemann et al reported that those adolescents who achieved ≥75 minutes VPA per week at ages 11,15 and 18 had significantly higher aBMD at the femoral neck at age 18 years [36]. This suggests that VPA undertaken at any point during adolescence may be the most effective intensity to improve bone mass.

Are there any differences or specific issues to be considered in respect to equalities?

Given the focus of the review on the physiological, mechanistic association between specific activities and muscle and bone development, differences across many equality groups are unlikely. However, there is a lack of any specific evidence regarding the significance of characteristics where there are potential differences, (that is sex and disability).

In respect to sex, the timing of puberty was highlighted as impacting the timing of bone mass development [1]. However, there is a lack of evidence regarding differential impacts and needs for bone and muscle development between the sexes.

Although not specifically covered in this review, there appears to be a lack of research into any changes in impact on bone and muscle health of ‘adapted’ versions of activities or into the benefits of non-mainstream activities more popular with disabled people.

Equality characteristics are more relevant to implementation of this evidence to support children and young people to undertake activities to improve bone and muscle. Although outside the scope of this review, it should be noted that there are differences in uptake of different activities across equality groups that should be considered[56].

What are the gaps in the current evidence base which should be addressed through further research?

From conducting this review of the evidence on physical activity and muscle and bone health outcomes in children and young people it is evident that several gaps in the evidence base exist. Below is a summary of some of the limitations identified which future research should seek to address and improve our understanding of the specific benefits of physical activity for children and adolescents, respectively.

Gaps in the evidence base include:

- high-quality longitudinal studies and RCTs to establish the causal relationship between activity/exercise interventions and bone health and muscle health outcomes
- research into the independent effect of muscle and bone strengthening activities on either bone health or muscular health
- studies focused specifically on maximising bone and muscle outcomes at the lower end of the pre-pubescent age range
- research examining differences in effectiveness of physical activity for maximising bone and muscle outcomes between the sexes
- dose response evidence to provide the optimal type, duration and intensity for muscle and bone health enhancing activities during childhood and at different pubertal stages of sexual maturation
- evaluations of the durability of shorter muscle and bone health enhancing interventions which may have more practical appeal
- evidence regarding the practicalities, compliance, and pedagogical considerations associated with designing a muscle and bone health enhancing programme have not been explored in the literature
- studies including non-active participants to establish effect of muscle and bone health enhancing activities and their potential for mitigating previous inactivity
- detail and specificity in the reporting of methodological protocols (for example details of measures used, outcomes assessed, and activities undertaken) suggesting that standardisation is needed to allow for comparability of future studies
- studies with children with physical disabilities to understand differences for ‘adapted’ versions of activities and non-mainstream activities more popular with disabled people

Summary

From this rapid review of the evidence on muscle and bone strengthening activities for children and young people, the strongest and most consistent evidence was found in support of the effect of weight-bearing physical activities, such as weight-bearing sports participation, in stimulating bone development. Activities which promoted bone health included soccer (football), jumping, martial arts and small-sided team games, with the strongest and most consistent evidence found for gymnastics. However, high intensity weight-bearing activities, with similar characteristics to those activities listed, may confer similar benefits. Although non-weight-bearing physical activities such as swimming and cycling were found to have little effect, they may be beneficial in mediating bone health through increases in lean soft tissue.

Evidence was found which supports the potential for a dose response relationship between physical activity and bone health. High volumes of habitual physical activity are associated with more favourable indicators of bone health, with evidence to suggest that increasing intermittent weight-bearing physical activity of any intensity to be beneficial. The evidence reviewed suggests that site specific benefits to bone strength may vary by the intensity of physical activity, although more research is needed to corroborate this.

The evidence base relating to muscular health outcomes is less developed and fewer studies were identified from the literature search. However, support was found for high impact small-sided games and circuit training for children, and traditional and plyometric resistance training in adolescents. Exposure to traditional resistance training may allow for preparation towards the transition into a popular form of physical activity conducted by adults. This review found support for different approaches to, and types of, interventions may be needed to promote muscular strength and bone heath to the age and sex of the child with the period around puberty (when maximal growth occurs) being the most effective time for bone adaptations, suggesting the period of 9 to 18 years of age being of greatest importance.

Although the relationship between activities and bone / muscle health is a physiological and mechanistic one, there are areas of consideration for equalities that need to be explored – in particular, differential impacts of activities and needs for bone and muscle differences across sexes, and the implications of adapted activities and the impacts of non-mainstream activities for disabled people.

A number of gaps exist within the evidence base which currently limit the ability to make firm conclusions about the benefits of specific type, duration and intensity of physical activity on bone health and muscular health outcomes for this age group. Improvements in research design, exposures used, population groups studied, measurement techniques employed and reporting of protocols would help to strengthen the evidence base. Standardisation of some of these parameters would more readily allow comparability between future studies.

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Appendix A

Table 2. Summary of the evidence in support of the review question 'What types of physical activities (including specific exercises/training and non-exercise activities) and at what intensity/frequency are effective in developing bone health in children and young people?'

No of studies/study design	No of participants, age	Summary of findings
2 Systematic reviews and meta-analyses [16,23]	9,238, range of mean ages 6.9 – 16.9 years	<u>Type of sport/activity</u> One systematic review and meta-analysis reported that short bouts of high-intensity weight-bearing activity can positively affect growing bone and can in some cases also improve lean and fat tissue. Trials that combined jumping activities with some other moderate-to-vigorous physical activity resulted in the greatest fat and lean mass changes, whereas the trials that were limited to jumping activities were more likely to report positive results for bone mass, but not for other body composition parameters [16] One systematic review and meta-analysis found that soccer practice during childhood provides positive effects on BMC and BMD compared to sedentary behaviour and other sports (such as tennis, weightlifting or swimming). Soccer players present higher BMC and BMD in most weight-bearing sites such as whole body, lumber spine, hip and legs [23]. <u>Frequency and duration</u> One systematic review reported that the most effective interventions included short (10- to 12-min) sessions of jumping exercises, executed 2 to 3 times per week [16].
5 Systematic reviews [17,25–27,29]	6,579, range of mean ages 7 - 17.2 years *unable to locate supplementary files for one review to obtain this data	<u>Type of sport/activity</u> One systematic review found gymnastics, soccer, capoeira and tennis to have more favourable outcomes than control groups [25]. Swimming was inferior not only to other sports but control groups. A consistent finding was that all studies examining gymnastics found more favourable effects on BMD and BMC compared to 'non-active' groups.

No of studies/study design	No of participants, age	Summary of findings
		One systematic review found significant osteogenic effects for taekwondo, judo, karate, kung fu, Kyokushinkai and boxing [29]. One systematic review found that drop jumping interventions during childhood and adolescence improve bone health parameters such as BMC BMD and bone structure. Moreover, these effects are maintained over time [17]. One systematic review found that male gymnasts (both recreational and elite) had better bone health outcomes compared with controls at central and peripheral skeletal sites, determined using different imaging modalities. Specifically, architecture, and strength of gymnasts' bones. Elite and recreational level gymnasts had higher total bone content at the radius, greater total and trabecular bone density at the radius, greater total and trabecular bone density at the radius and tibia, larger bone size at the hip and radius, a thicker radial cortex, and higher estimates of bone strength at the hip and radius. Although not conclusive, there was evidence for gymnasts to have higher bone density and bone mineral content, larger muscles and bones, and greater estimates of bone strength compared with controls [26]. Similar support for gymnastics was reported in another systematic review which concluded that gymnasts present higher bone mineral values in comparison with untrained controls. The osteogenic effect of gymnastics has a positive influence on bone mineral accrual and overcomes the possible negative influence of high athletic activity that may cause negative energy balance and low body fat mass which are associated with lower bone accrual [27]. <u>Frequency</u> One systematic review suggests that 10 mins of (drop) jumping twice a week may be enough to improve bone mineral content among children and adolescents [17].

No of studies/study design	No of participants, age	Summary of findings
		Duration One systematic review examined interventions which ranged from 10 weeks to 2 years and longer interventions showed more favourable increases in bone quality and quantity [17]. Authors suggest that as little as a 3-month intervention may begin to be beneficial to bone mass and produce increases in BMC.
2 Randomised controlled trials [31,57]	1,729, range of mean ages from 6 to 10 years	Type of sport/activity One RCT found that small-sided games and circuit strength training of 3 x 40 mins a week for 10 months improved bone mineralisation (whole body aBMD and leg BMC [31]. Vigorous activity One RCT found a significant and favourable improvement in children's weight-bearing factor scores following a bone strengthening intervention (involving 20 min of vigorous activity 3 days per week with a 5 min jumping component) delivered for 85 minutes 5 times a week for 20 weeks for 2 years [57].
8 Longitudinal studies [18–20,28,33,35–37]	6,880, range of mean ages from 8-23	Type of sport/ activity One study found mean estimated differences in bone mass between different trajectories of sports participation in boys were larger and more consistent across anatomical sites compared to girls. Boys and girls who were consistent sports participators had greater leg BMC than those who dropped out. There may also be skeletal benefits (whole body BMC) for boys who only start sport in the adolescent period ~14 years of age even if they have not previously participated [19]. Similarly, former male interscholastic sport participants and female interscholastic power sport participants (members of basketball, cheerleading, football, gymnastics, soccer and/or volleyball teams for at least 2 seasons) were found to have stronger bones than their peers even when adjusting for current PA and muscle power [18]. One study reported aBMD in the left (p value = 0.022) and right legs (p value = 0.013) to be higher among adolescents engaged in weight-

No of studies/study design	No of participants, age	Summary of findings
		bearing sports (basketball, tennis, gymnastics, judo, kung fu, karate) than in swimmers [20]. Furthermore, the study identified that changes in LST were the most relevant determinant of areal BMD accrual in the lower limbs, mainly among adolescents engaged in sports. Independently of fat mass, changes in LST explained 54% and 58.5% of all variances observed in bone accrual in the left and right legs, respectively [20]. One study examining the impact of artistic gymnastics on bone outcomes reported that gymnasts, after a 12-month follow-up, demonstrated a higher BMD in the Ward's triangle and whole femur than the controls, as well as an improvement in femur density. In addition the gymnasts had significant bone accrual (after 12 months) in the upper limbs, lower limbs, and whole body [28]. <u>Moderate to vigorous physical activity</u> MVPA was a positive independent predictor of bone strength in one longitudinal study, with findings show a significant positive association between habitual MVPA with bone strength at the distal radius [37]. <u>Vigorous physical activity</u> One study reported an accumulative impact of VPA on bone strength outcomes throughout adolescence and into emerging adulthood. On average accumulating 5 mins per day more VPA was associated with up to 3% greater bone structural outcomes by age 19 in boys and up to 5.1% greater bone structural outcomes in girls [35]. One study found that vigorous physical activity was more strongly related to aBMD than moderate physical activity in both sexes. The association of vigorous-intensity physical activity with aBMD was independent of the impact of physical activity [36].

No of studies/study design	No of participants, age	Summary of findings
		Dose of activity (volume and intensity) One longitudinal study [33] identified variation in bone health across the activity volume and intensity distribution of an individual's activity profile with intensity being key for aBMD and BMC and higher volumes of lower intensity activity potentially beneficial for hip structural geometry. Independent associations of the intensity gradient confirmed the importance of high intensity physical activity for optimal BMC and aBMD, additive associations of volume and intensity suggest that increasing physical activity of any intensity could also be advantageous for hip aBMD and total body BMC. For spine aBMD vigorous intensity physical activity was key in males, but no associations were evident in females. For the hip structure analysis outcomes, large volumes of physical activity accumulated at relatively low intensities were important even if vigorous intensity activity was absent or low.
1 Narrative systematic review [21]		Type of sport/activity One narrative review reported significant benefits of weight-bearing non-elite sports on cQUS outcomes. High-impact weight-bearing sports, such as soccer playing and gymnastics or dancing, were associated with the greatest benefits for bone health. Swimmers and cyclists were not at any apparent bone advantage compared to controls [21].
8 Cross-sectional studies [22,24,30,32,34,38,39,58,59]	927, range of mean ages 8.07 – 18 years	Type of sport/activity One study showed a greater increase in bone mineral density within a school-based martial arts group (judo, jiu-jitsu, karate, taekwondo, boxing and muay thai) compared to those who only undertook usual PE [30]. One study reported that adolescent male footballers exhibited higher bone density, geometry, and stiffness compared with swimmers, cyclists and controls. Although swimmers and cyclists had higher bone outcomes compared with controls, these differences were not significant [24].

No of studies/study design	No of participants, age	Summary of findings
		One study found favourable BMD outcomes (5-9% higher compared to control) for girls who participated in 1.5 hours of sports training (volleyball, basketball, handball) 2 x/wk for 6 months [22]. Moderate to vigorous physical activity One study reported that the highest tertile of MVPA (approximately > 77 min MVPA/day) showed significantly higher bone stiffness index compared with the groups with < 77 min MVPA/day in boys. Although no significant association with MVPA was found in girls, there were positive dose–response trends across MVPA levels for bone stiffness index in both boys and girls [38]. Furthermore, one study found that more than 78 minutes/day of MVPA was associated with increased BMD at the femoral neck. Vigorous physical activity One study reported that VPA presented the strongest relationship with bone mineral parameters; being the only intensity with statistically significant relationships with whole body and lumbar spine BMC values and the highest correlation coefficients with femoral neck BMC and BMD [34]. One study reported that in order to guarantee optimal bone health, more than 19 minutes/day of VPA with increased BMC at the hip and more than 28 and 32 minutes/day of VPA with increased BMD at the intertrochanter and femoral neck [39] Overall physical activity One study [32] reported positive associations of both cortical and trabecular vBMD and BMC independent of BMI, chronological age, and bone age, suggesting that a high dose of physical activity is related to a continuous osteogenic response during preadolescence. This was supported by another study which found that overall physical activity also indicated significant relationships with whole body and

No of studies/study design	No of participants, age	Summary of findings
		femoral neck BMC and BMD suggesting that volume may also play a role in bone development [34].

Bone measures included: bone mineral density (BMD), bone mineral content BMC), bone area, cross-sectional area, cross-sectional movement of inertia, femoral neck width, femoral neck diameter, subtotal body, stiffness index (SI), hip strength index and hip structural analysis (HAS), total body BMD, BMD of arms, leg, femoral neck, total proximal femur, hip, total spine and lumbar L1-L4.

Bone outcomes were measured objectively by: Dual energy X-ray absorptiometry (DXA), Computed tomography (CT), ultra-sound, peripheral quantitative computed tomography (pQCT), Hip Structure analysis (HSA), Single photon absorbency (SPA), Calcaneal quantitative ultrasound (cQUS) and amplitude dependent speed of sound.

Physical activity was measured using accelerometry and self-report questionnaire
The type, duration and frequency of the physical activity varied widely and reported as: number of sessions, length of training, specific individual activities, minutes spent in moderate physical activity (MVPA) and/or vigorous physical activity (VPA), weight-bearing or non-weight-bearing, osteogenic sport or non-osteogenic sports and Physical Education.

Lean and fat tissue outcomes included: lean mass, lean soft tissue (LST) fat free soft tissue, fat mass, %body fat, Body Mass Index (BMI), measured using DXA and skinfolds.

Table 3. Summary of the evidence in support of the review question 'What types of physical activities (including specific exercises/training and non-exercise activities) and at what intensity/frequency are effective in developing muscle health in children and young people?'

No of studies/study design	No of participants, age	Summary of findings
1 Systematic review and meta-analysis [40]	6,652 range of mean ages 8.2 – 19 years	Type of activity Traditional and plyometric methods of resistance training appear to be the most effective form of PA delivery in adolescent boys [40]. Duration The literature suggests that MF interventions lasting 8–12 weeks are most effective in adolescent populations although authors acknowledge that intervention duration may not have been long enough in over a quarter of studies to evoke an efficacious response [40].
2 Randomised controlled trials [31,41]	439, mean age 8 - 12.47 years	Type of activity One RCT reported that a movement orientated functional strength training programme (in comparison with a traditional strength training program) may be more effective on improvements of movement quality, muscular strength, flexibility, and power in adolescent girls [41]. One RCT showed school-based training interventions with small-sided ball game and circuit strength training improved, jump performance and postural balance over a 10-month period in school children aged 8–10 years, suggesting that high-impact PE sessions can be used to promote musculoskeletal health in young children [31].
3 Cross-sectional studies [42,43,60]	200, range of mean ages 10-13 years	Type of training One study reported more favourable training induced gains in muscular power as a result of resistance training programme (45 mins of medicine ball throws, jumps onto a box, plyometric jumps, and sets of 30-to-40-m-speed runs, 2x/wk for 8 weeks) compared to suspension training [42]. One study reported significant improvements in both the flexor and extensor trunk muscles for a sample of high school students following a Pilates training programme (2 x 55 min sessions/wk for 6 wks) [43].

No of studies/study design	No of participants, age	Summary of findings
		One study found that both dominant and nondominant leg press training (3 x/wk for 8 weeks) significantly increased both ipsilateral and contralateral lower body strength and power in a sample of adolescent boys [60].

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[2] **Muscular outcomes included**: Upper limb muscular fitness, lower limb muscular fitness, muscular fitness, isometric strength of the trunk extensor muscles, strength of the trunk flexor muscles, upper body strength and lower-body strength.

Muscular outcomes were measured by: National Physical Fitness and Health Standards fitness tests, Functional Movement screen test, standing long jump, Sorensen test, Bench Trunk curl test, Medicine ball throwing, standing long jump and countermovement vertical jump, maximum voluntary isometric contraction of knee extensors and flexors, triple hop test, MVIC strength of elbow flexors and handgrip and stork and Y balance test.

Table 4. Summary of the evidence in support of review question 'What are the health benefits of muscle and bone strengthening activities in children and young people?'

No of studies/study design	No of participants, age	Summary of findings
1 Systematic review and meta-analysis [16]	6,196, range of mean ages 6.9 – 15.04 years	Bone outcomes Meta-analyses revealed a small positive effect of bone-targeted exercise on whole body BMC (standardized mean difference [SMD] = 0.483, 95% CI = 0.132–0.833), femoral neck BMC (SMD = 0.292, 95% CI = 0.022 to 0.607), lumbar spine BMC (SMD = 0.384, 95% CI = 0.193–0.575), Lean and fat tissue outcomes Meta-analyses revealed a small positive effect of bone-targeted exercise on fat mass (SMD = 0.248, 95% CI = 0.406 to 0.089). Lean mass observations were equivocal with considerable variation in lean mass outcomes between trials.
2 Systematic reviews [45,46]	7,066, range of mean ages 6 months -18 years	Bone outcomes One systematic review reported that young children who engaged in bone-strengthening activities or in high levels of total physical activity have stronger bones. Strong evidence demonstrates that higher amounts of physical activity are associated with more favourable indicators of bone health in children ages 3-6. However, the data did not point to a specific dose of activity that was needed to produce these benefits [45]. One systematic review reported those children assigned to exercise interventions had significantly greater increases in BMC and aBMD but not bone area, than children assigned to control groups. The overall mean difference between the percent change in BMC in the intervention and control groups was 0.8%(95%CI, 0.3–1.3; p = 0.003) for total body; 1.5% (95% CI, 0.5–2.5; p = 0.003) for femoral neck; and 1.7% (95% CI, 0.4–3.1; p = 0.01) for spine [46].
2 Cross-sectional studies [47,48]	780, range of mean ages 10-16 years	Psychological outcomes One study reported no independent association between muscular fitness and mental health (wellbeing and internalising problems) in older adolescents [47].

No of studies/study design	No of participants, age	Summary of findings
		One study reported that muscular strength was associated with psychological distress (that is stress and negative affect) and psychological well-being (that is optimism and self-esteem). Children with higher muscular strength showed lower levels of stress and of negative affect and higher levels of optimism and self-esteem [48].

[3] **Muscular fitness was assessed as**: upper body muscular strength and lower body muscular strength measured using standard protocols 90 degree push up or handgrip strength and standing long jump respectively.

Psychological outcomes included: stress and negative effect as well as mental health (wellbeing and internalising problems) were measured using validated questionnaires.

Bone outcomes included: bone mineral content (BMC), bone mineral density (BMD), volumetric BMD, bone area, bone structure, periosteal and endosteal circumference, hip structural analysis, and bone quality, measured using: dual- energy x-ray absorptiometry (DXA), quantitative ultrasound (QUS), peripheral quantitative computed tomography (pQCT)

Lean and fat tissue outcomes included: absolute fat mass, absolute lean mass (LM), fat free soft tissue, percentage body fat (%BF), body mass index (BMI) measured using dual energy X-ray absorptiometry and calliper-based anthropometry

Physical activity was assessed using: accelerometry, heart rate monitoring, direct observation as energy expenditure via doubly labelled water, parental report and researcher delivered intervention

Table 5. Summary of the evidence in support of the review question 'Are there any particular groups within the 5-18 age range where muscle and bone strengthening activities have the highest impact on bone strength and potential for mitigating previous inactivity?'

No of studies/study design	No of participants, age range	Summary of findings
1 Systematic Review [46]	2,577, range of mean ages 3-18 years	Pubertal status Benefit of exercise was limited to children who were prepubertal (bone mineral content: total body [0.9; 95% CI, 0.2–1.7; p = 0.01], femoral neck [1.8; 95% CI, 0.0–3.5; p = 0.047], spine [3.7; 95% CI, 0.8–6.6; p = 0.01], and aBMD: femoral neck [0.6; 95% CI, 0.1–1.2; p = 0.07], spine [1.5; 95% CI, 0.7–2.3; p<0.001]), with no differences among children who were pubertal (all p >0.05) Sex Changes in aBMD did not differ by sex (all p <0.05), although the number of studies providing male- specific results was small (6 of 22 eligible studies included boys).
3 Longitudinal Studies [36,53,61]	6,493, range mean ages 10-25 years	Maturation In one study, the osteogenic sports participants (OS) and non-osteogenic sports (NOS) participant groups showed a linear increase in all bone outcomes from −2 to +2 years from PHV. OS group had greater BMC, HSA estimates, TBS and stiffness index at a given years from PHV compared to NOS group. Furthermore, the differences in bone outcomes between OS and NOS groups increased with biological age [61]. Similarly, one study found the greatest gains in BMD for both boys (0.139 $g/cm^2/y$; 95% CI, 0.127-0.151 $g/cm^2/y$) and girls (0.106 $g/cm^2/y$; 95% CI, 0.098-0.114 $g/cm^2/y$) observed between the year before and 2 years after PHV [53]. Despite faster gains, older age at puberty was associated with persistently lower BMD [53]. The magnitudes of faster gains were greatest between ages 14 and 16 years in both male participants (0.013 $g/cm^2/y$; 95% CI, 0.011-0.015 $g/cm^2/y$) and female participants (0.014 $g/cm^2/y$; 95% CI, 0.014-0.015 g/cm2/y), were greater in males between ages 16 and 18 years, and were least in both males and females between ages 18 and 25 years.

No of studies/study design	No of participants, age range	Summary of findings
		Vigorous physical activity One study found that those who achieved ≥ 75 minutes per week at 11,15 and 18 years had significantly higher aBMD at age 18 years. Results were more consistent in boys, but engagement in vigorous activities from the middle to the end of adolescence seems to be related to higher values of femoral neck aBMD suggesting any point of adolescence is a window of opportunity to increase bone mass [36].
2 Cross-sectional Studies [50,55]	212, range of mean ages 5.09 - 18 years	Maturation One study reported more favourable femoral neck BMD in peripubertal males and females than their postpubertal peers and femoral neck BMC was also higher in peripubertal females than in postpubertal females after adjusting by the same covariates [55]. Meeting the aerobic physical activity recommendation No association was found between parental reported physical activity and bone mineral density in a sample of 5 year olds. [50].

[4] Data were collected cross-sectionally

Physical activity was measured using accelerometers and surveys (including proxy survey and/or interview using questions from validated physical activity questionnaires for example the International Physical Activity Questionnaire

Bone outcomes included: whole body bone mineral density, bone mineral density (BMD), bone mineral content (BMC), bone area and areal bone mineral density (aBMD), lumber spine and femoral neck aBMD, bone area (BA), Cortical area (CortAr), Cortical thickness (CortThk), volumetric bone mineral density (vBMD), periosteal circumference (PC), endosteal circumference (EC), hip structural analysis, trabecular bone score (TBS), bone stiffness

Bone outcomes were measured by: dual photon absorptiometry (DPA), dual energy x-ray absorptiometry (DXA), or peripheral quantitative CT (pQCT) or quantitative ultrasound (QUS)

Maturation was assessed by: years from peak height velocity (PHV) measured using age and height in a validated algorithm