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THE IMPACT OF SEDENTARY BEHAVIOR AND PHYSICAL ACTIVITY ON BONE HEALTH: A NARRATIVE REVIEW FROM THE REHABILITATION WORKING GROUP OF THE INTERNATIONAL OSTEOPOROSIS FOUNDATION

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Abstract

Physical activity (PA) and sedentary behavior (SB) are two key lifestyle factors with profound implications for bone health across the lifespan. While PA is recognized for its positive effects on bone mineral density (BMD) and fracture prevention, emerging evidence highlights the detrimental consequences of prolonged sedentary time, independent of PA levels. This review synthesizes current knowledge on the impact of PA and SB on bone health outcomes, focusing on BMD and fracture risk in children, adolescents, adults, and older populations. A selection of epidemiological studies, systematic reviews, and meta-analyses was analyzed to explore the associations between movement behaviors and bone health indicators across different life stages. Particular attention was given to studies objectively measuring SB and PA and to the substitution effects of sedentary time with light or moderate-to-vigorous PA. In children and adolescents, higher levels of SB are associated with lower BMD, particularly at weight-bearing sites, while participation in weight-bearing and impact-loading PA positively influences bone mass accrual. In adults and older individuals, regular PA, including moderate-to-vigorous intensity weight-bearing PA and resistance training activities, is consistently linked to greater BMD and reduced fracture risk. Conversely, high sedentary time is associated with lower BMD and increased fracture incidence, particularly among frail or pre-frail individuals. Importantly, replacing sedentary time with even light-intensity PA yields measurable benefits for bone health, particularly among older adults and postmenopausal women, and may contribute to a reduced risk of fractures, although

evidence remains limited. Promoting PA while minimizing SB should be central to clinical practice and public health policies aimed at maximizing and preserving skeletal health and preventing osteoporotic fractures, across the lifespan. Early intervention, continuous promotion across life stages, and adherence to WHO guidelines offer an effective, evidence-based framework for lifelong bone health maintenance.
Keywords Sedentary behavior · Physical activity · Bone health · Fracture · Osteoporosis

Introduction

Physical activity (PA), as defined by the World Health Organization (WHO), encompasses any bodily movement produced by skeletal muscles that requires energy expenditure [1]. This includes activities undertaken while working, playing, carrying out household chores, traveling, and engaging in recreational pursuits. Regular PA is recognized as a cornerstone for the maintenance and improvement of health throughout the life course [2]. It plays a vital role in preventing non-communicable diseases, enhancing mental health, and promoting musculoskeletal integrity. In contrast, sedentary behavior (SB) is characterized by the Sedentary Behavior Research Network as any waking behavior involving an energy expenditure of ≤ 1.5 metabolic equivalents (METs) while in a sitting, reclining, or lying posture [3]. Common sedentary behaviors include activities such as prolonged sitting, television viewing, computer use, and passive transportation. Importantly, SB is distinct from physical inactivity: an individual may meet recommended PA guidelines yet still accumulate high amounts of sedentary time, potentially exposing themselves to health risks [4].

Emerging theoretical perspectives conceptualize SB as potentially addictive in nature. Drawing on behavioral science, some models liken the habitual and compulsive aspects of SB, particularly screen-based or passive entertainment activities, to mechanisms observed in substance use and behavioral addictions. For instance, a systematic review examined associations between movement behaviors and substance use in adolescents and emerging adults and found that SB was positively associated with alcohol and cannabis use among adolescents, indicating that SB might serve as a risk marker for substance use [5]. This framework may explain the difficulty individuals have in breaking prolonged patterns of SB, even when aware of the associated health risks.

The distinction between PA and SB is particularly relevant when considering skeletal health. Bone is a dynamic tissue that adapts to mechanical loads, and both the presence and absence of mechanical stimuli can have profound effects on bone structure and strength [6]. Mechanical loading promotes osteogenesis through the activation of osteoblasts and the inhibition of osteoclast-mediated resorption, primarily via mechanotransduction pathways such as Wnt/β-catenin signaling. While PA, particularly weight-bearing and high- impact exercise, stimulates bone formation and maintenance, prolonged SB may conversely contribute to bone loss and an increased risk of osteoporosis. Given the contrasting influences of PA and SB on bone health, it is essential to better understand their respective impacts. This article will explore the current evidence regarding how PA and sedentary lifestyles affect bone health and fracture risk, across different populations and life stages.

Children, Adolescents, and Young Adults

The period of childhood, adolescence, and early adulthood represents a critical window for the accumulation of peak bone mass, a major determinant of future osteoporosis risk. Lifestyle behaviors during these phases, notably PA and SB, appear to exert significant influences on bone development. Several studies have investigated the relationship between sedentary time and bone outcomes in young populations. In a systematic review, Koedijk et al. highlighted that objectively measured SB, assessed primarily via accelerometry, was negatively associated with bone health at weight-bearing sites such as the femoral neck [7]. This association was small in magnitude but independent of moderate-to-vigorous PA (MVPA) levels. Interestingly, no significant relationship was observed between sedentary time and lumbar spine or total body bone parameters. Notably, studies relying on subjective assessments of SB (e.g., questionnaires) failed to detect consistent associations, emphasizing the importance of objective measurement tools. Expanding on these findings, Christofaro et al. demonstrated that higher total screenbased SB was associated with lower whole-body bone mineral density (BMD) in a cohort of Brazilian children and adolescents after adjustment for sex, age, maturity offset, lean mass, and PA [8]. Specifically, youth with lower total SB exhibited significantly greater whole-body and leg BMD compared to their peers with higher SB levels. However, the observed associations were attenuated after adjusting for PA levels, which could reflect the complex interplay between movement behaviors and bone health. This attenuation may also be partially due to model specification issues, such as multi-collinearity between SB and PA, which are often inversely correlated. This concern is particularly relevant when self-reported measures of SB and PA are used, as they are prone to recall bias and lower measurement accuracy. In addition, in that study, no adjustment was performed for nutrition intake or obesity which could confound the observed associations.

While excessive sedentary time appears detrimental, engaging in weight-bearing physical activities confers clear osteogenic benefits. Behringer et al., through a meta-analysis of 27 studies, confirmed that weight-bearing activities such as jumping and resistance training significantly enhance both bone mineral content (BMC) and BMD in growing individuals [9]. Although the effect sizes were modest, the findings underscore that even relatively small improvements in bone mass during youth could have substantial long-term benefits [10]. Moreover, calcium intake and maturational status emerged as important moderators, highlighting the multifactorial nature of skeletal development. Supporting the long-term value of early interventions, Mayer et al. reported that children who participated in a nine-month school-based PA program maintained significantly higher BMC and BMD at key skeletal sites (i.e., total body, femoral neck, and total hip) three years after the cessation of the intervention [11]. These effects corresponded to approximately 6–8% higher bone values compared to non-intervention controls. However, adjustments for PA at follow-up attenuated the observed benefits, suggesting that continuous engagement in PA is essential for sustained skeletal advantages. Interestingly, Herrmann et al., in the IDEFICS study, further demonstrated that objectively measured moderate-to-vigorous PA was positively associated with bone stiffness in children aged 2 to 10 years [12]. Participation in weight-bearing exercise was linked to 2–3% higher stiffness index values, while greater sedentary time showed a negative, though partially attenuated, association with bone stiffness after accounting for MVPA levels. These results reinforce the critical importance of promoting active lifestyles from the earliest years to support optimal bone health trajectories.

Together, these studies converge to suggest that while SB independently exerts small but measurable adverse effects on bone health in youth, participation in regular, weightbearing PA can significantly promote bone strength and structure. Early-life interventions and sustained engagement in vigorous and impact-loading activities represent essential strategies to optimize skeletal development and potentially mitigate the future burden of osteoporosis.

Adults and Older Adults

PA and SB are key modifiable factors influencing BMD, an essential determinant of skeletal integrity and fracture risk. Some evidence exists to support the notion that lifestyle behaviors impact BMD in adult and older populations. A systematic review by McMichan et al. evaluated the association between SB and BMD in adults aged 65 years and older [13]. Although findings varied, the review suggested that greater sedentary time may be negatively associated with BMD, particularly at weight-bearing sites such as the femoral neck and pelvis. Interestingly, sex differences emerged, with men showing predominantly negative or no associations, while results were more heterogeneous among women. The limited and varied data underscored the need for more high-quality prospective studies that incorporate sophisticated exercise tracking devices to clarify the independent effects of SB on bone health in this age group. In a complementary study focusing on postmenopausal women, Chopra et al. compared PA and SB patterns between individuals with normal and low total hip BMD [14]. Women with lower hip BMD exhibited longer sedentary bouts and less evenly distributed PA throughout the day. Notably, 58% of sedentary time in the low BMD group occurred in prolonged bouts lasting ≥ 20 min, underscoring that not only total sedentary time but prolonged uninterrupted sedentary periods may be detrimental to bone health. The positive role of PA, especially at moderate-to-vigorous intensity, has been reinforced by Kim et al., who analyzed data from the Korea National Health and

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Nutrition Examination Survey [15]. Their study found that moderate-to-vigorous PA was positively associated with hip BMD in men aged over 50, whereas no significant associations were observed in women. This highlights potential sex-specific differences in skeletal responsiveness to physical stimuli and suggests that PA intensity may be a critical determinant of bone adaptation in older adults. In addition to the intensity of PA, participation in sports and exercises that involve greater amounts of high-impact movements appears to contribute to higher BMD in young and older adults [16, 17]. Building on the topic of high-impact PA, it is interesting to observe that a meta-analysis reported a significant effect of whole-body vibration, when delivered at high frequency, low magnitude, and with a high cumulative dose, on BMD in postmenopausal women [18].

Expanding on the role of structured exercise, Mohebi et al. conducted an updated systematic review and meta analysis focusing on postmenopausal women [19]. Their results provided evidence that exercise interventions, regardless of menopausal timing or bone status, produce small-to- moderate improvements in BMD at the lumbar spine, femoral neck, and total hip, as previously suggested [10]. Notably, the effectiveness of interventions appeared independent of whether they were supervised or unsupervised, reinforcing the broad applicability of exercise programs for bone health promotion. Specific attention to exercise modality was given in the meta-analysis by Shojaa et al., who focused exclusively on dynamic resistance training [20]. This training was shown to induce significant, albeit moderate, improvements in lumbar spine and hip BMD. Subgroup analyses appeared to show larger BMD gains with lower net training frequency (< 2 sessions/week) compared with ≥ 2 sessions/ week. However, the authors stressed that this counterintuitive result is likely an artifact of limited variability in training frequency (≈1.5–3.5 sessions/week), small subgroup numbers, and other methodological limitations and thus does not support a firm recommendation on optimal frequency. By contrast, they did find that free-weight training was superior to machine-based training for BMD, at least at the total hip. Anyway, these findings support the integration of resistance exercises into osteoporosis prevention and management strategies. Finally, in a novel approach, Ricci et al. applied an isotemporal substitution model to examine the potential benefits of replacing sedentary time with light PA in women over 50 years [21]. Their results indicated that substituting just 30 min of sedentary time with light activity was associated with a 3 mg/cm^2 increase in BMD and a 12% reduction in the odds of having (or being diagnosed with) osteoporosis, particularly at the spine. The benefits were even greater in overweight and older women, suggesting that even light-intensity activities such as casual walking or household tasks could meaningfully contribute to bone health in aging populations. These findings align with the broader literature on isotemporal substitution, a modeling approach pioneered by Mekary et al. that evaluates how reallocating time from SB to PA influences health outcomes [22]. Mekary et al. demonstrated that replacing 30 min/day of brisk walking with 30 min/day of jogging/ running was associated with more weight gain (+ 1.57 kg; 95% CI 0.33 to 2.82), whereas replacing 30 min/day of slow walking with brisk walking was associated with less weight gain (- 1.14 kg; 95% CI - 1.75 to - 0.53) and even greater benefits when brisk walking displaced television watching. Although few studies have applied the isotemporal substitution models specifically to bone health, the same principle suggests that even short bouts of activity (e.g., 30 min/ day of brisk walking instead of sitting) could translate into meaningful improvements in BMD or reduced fracture risk. Future research should use the isotemporal substitution models to quantify these effects for skeletal health.

While BMD serves as a crucial biomarker of skeletal health, other measures of bone structure are similarly important for determining bone fragility and fracture risk. A systematic review and meta-analysis reported that greater amounts of high-impact PA are associated with improved total and trabecular volumetric BMD, as well as cortical thickness [23]. However, understanding how SB and PA influence fracture risk is therefore essential to fully grasp the burden of a sedentary lifestyle and the protective role of movement on skeletal resilience [24]. Several large cohort studies have investigated the association between PA, SB, and fracture incidence among older adults, providing important insights into prevention strategies. In the Women's Health Initiative (WHI) cohort study, LaMonte et al. assessed the relationship between self-reported PA, SB, and fracture risk among over 77,000 postmenopausal women [25]. Over a mean follow-up of 14 years, higher levels of total PA were associated with a significantly lower risk of hip fractures (hazard ratio [HR] for > 17.7 MET-hours/ week vs none, 0.82; 95% CI, 0.72–0.95). Benefits were also observed for other forms of physical activity, including walking, mild activities, and yard work. Notably, mild PA was associated with reductions in vertebral fractures and total fractures. However, a modest

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positive association between moderate-to-vigorous PA and wrist fractures was detected, likely reflecting increased fall risk among more active individuals. Furthermore, sedentary time exceeding 9.5 h per day was associated with an increased risk of total fractures (HR, 1.04; 95% CI, 1.01–1.07), even after adjustment for PA levels. Importantly, higher PA appeared to partially offset the increased fracture risk associated with prolonged SB. Similarly, findings from the Nurses' Health Study support the protective role of PA against fractures [26]. Indeed, Feskanich et al. prospectively followed over 61,000 postmenopausal women for 12 years and reported that each additional 3 MET-hours per week of leisure-time activity (approximately equivalent to 1 h of walking) was associated with a 6% lower risk of hip fracture. Women in the highest quintile of self-reported PA, defined as engaging in at least 24 MET-hours per week of activity, exhibited a 55% reduced risk compared to participants in the lowest quintile of PA (< MET-hours/week). Walking alone, even in the absence of other structured exercise, conferred substantial protection: walking at least 4 h per week was linked to a 41% lower risk of hip fracture compared to walking less than 1 h per week. These results reinforce the notion that moderate, accessible activities such as walking can have some effects on fracture prevention. However, it should be noted that while walking remains a widely accessible and beneficial form of PA in older frail adults, its specific impact on fracture prevention in the general population appears more contrasted [27, 28]. Several meta-analyses and expert consensus suggest that walking alone may not be sufficiently osteogenic to significantly reduce fracture risk, especially at critical skeletal sites [27, 28]. In contrast, structured balance, functional, and resistance exercises have demonstrated greater efficacy in reducing fall risk and enhancing bone strength, thereby offering more direct protection against fragility fractures [19, 29]. Nevertheless, observational evidence still supports a modest protective role of regular walking against hip fractures in older adults, particularly among those who are otherwise sedentary. In addition, Zhou et al. conducted a large analysis of over 413,000 adults from the UK Biobank to examine the interplay between frailty status, SB, and fracture risk [30]. Their results demonstrated that both pre-frailty and frailty were independently associated with an increased risk of total, hip, vertebral, and other fractures. Importantly, SB significantly amplified these associations: participants with higher sedentary time (≥ 6 h/day) exhibited a stronger relationship between frailty status and fracture risk compared to those with lower sedentary exposure. These findings underscore that SB not only directly increases fracture risk but also exacerbates vulnerabilities among frail or pre-frail individuals. Recent qualitative and feasibility research has shed light on how older adults who are pre-frail or frail perceive their own sedentary behaviors and the barriers they face in reducing them. Rodrigues et al. highlighted that many frail individuals rationalize sedentary time based on purpose (e.g., leisure or health-related constraints), suggesting that interventions should distinguish between "purposeful" and "passive" sedentary time to increase acceptability and adherence [31].

Clinical Implication and Public Heath Recommendations

The growing body of evidence linking SB and insufficient PA to poorer bone health and increased fracture risk across all ages emphasizes the need for clinical vigilance throughout the life course. Healthcare professionals should systematically incorporate the assessment of PA levels and sedentary habits into routine clinical evaluations, not only among older adults but also in children, adolescents, and younger adults. Early interventions aimed at promoting PA during the critical periods of bone mass accrual, coupled with strategies to limit sedentary behaviors, are essential to optimize peak bone mass and reduce future fracture risk. For adults and aging populations, maintaining or increasing physical activity, particularly weight-bearing and resistance exercises, remains crucial for preserving bone health. It is noteworthy that the WHO recommendations on PA and SB, which advocate regular moderate-to-vigorous activity and minimizing sedentary time, align perfectly with the needs for bone health promotion across the lifespan [32]. Thus, from a bone health perspective, following the WHO guidelines offers a highly effective preventive strategy. Clinical guidelines should integrate this life-course perspective, promoting both increased activity and reduced sedentary time as central pillars in the maintenance of skeletal health. Recently, however, PA recommendations have shifted to focus on 24-h movement guidelines, with increasing recognition that PA, SB, and sleep are interdependent behaviors [33]. One study to date, including almost 3,000 older men in the MrOS cohort, has reported that higher proportions of SB relative to the proportion of PA and sleep were associated with higher odds of recurrent fractures [34].

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It is also important to note that SB is not only shaped by societal factors but also by individual comorbidities, particularly in adults at elevated risk of falls and fractures. A history of falling or sustaining a fracture frequently leads to a heightened fear of recurrence. This fear is especially prevalent among individuals with compromised bone health, such as those with osteoporosis, due to their increased vulnerability linked to low BMD, muscle weakness, and impaired balance [35]. As a result, many adopt avoidance behaviors (i.e., limiting their movements to reduce perceived risk) which inadvertently increase sedentary time [36]. Importantly, SB is both a consequence and a predictor of future falls, creating a self-reinforcing cycle: fear of falling leads to inactivity, which exacerbates muscle deconditioning and balance deficits, thereby heightening fall risk and reinforcing the initial fear [37]. This association was recently confirmed in a 2022 systematic review and meta-analysis of over 24,000 older adults, which reported that higher sedentary time was significantly associated with an increased risk of falling (OR = 1.17; 95% CI: 1.07–1.28) [38]. Psychological factors such as anxiety and depression, more common in sedentary individuals and those fearful of falling, further reduce selfefficacy and motivation to engage in PA. Numerous studies, however, have shown that regular PA can break this cycle by improving strength, balance, and confidence, thereby reducing the risk of future falls [39].

Despite growing awareness, certain societal trends continue to inadvertently reinforce sedentary lifestyles. For example, urban planning policies that prioritize motorized transportation use over active transport, the widespread digitalization of work and education, the decrease of regular PA from public education, and even some 'smart' home technologies all contribute to a reduction in physical activity in daily life. Ironically, public initiatives aimed at technological advancement and digital inclusion, while beneficial in many ways, often promote prolonged screen time and passive leisure activities. Recognizing and addressing these conflicting pressures is essential to formulating

truly effective public health strategies that promote PA while actively countering the systemic drivers of SB. At the population level, a comprehensive public health strategy is warranted to address the dual challenges of low PA and high SB impacting bone health. Policies and programs should target all age groups, starting with initiatives in early childhood to instill active habits and minimize excessive screen time, through to adolescence, adulthood, and older age [40]. Schools, workplaces, and community settings should be designed to promote daily movement, integrating active breaks, encouraging active transportation, and ensuring accessible opportunities for recreational PA. For example, activity-focused educational and pedagogical programs delivered by school teachers have demonstrated effectiveness in increasing PA and reducing SB in children, both at school and in the home [41]. In adults, workplace approaches including personalized behavioral change interventions, standing/active workstations, and promoting stair use can also improve PA and SB [42]. To enhance the design and reporting of such interventions, the use of standardized behavior change taxonomies can be valuable. The Behavior Change Technique (BCT) Taxonomy v1, developed through international consensus, classifies 93 distinct techniques into a structured framework, supporting the transparent description and replication of behavior change strategy [43]. Applying this taxonomy can strengthen the theoretical underpinnings of PA and SB interventions, improve comparability across studies, and inform scalable public health solutions.

For the older adult, given that prolonged sedentary time disproportionately affects frail individuals, especially during colder seasons, integrating seasonally adapted, context-sensitive interventions may enhance engagement and effectiveness [44]. Public health messaging must encourage that both higher levels of PA and reduced sedentary time are independently beneficial for bone health. In this regard, the WHO's global recommendations, i.e., advocating at least 60 min per day of moderate-to-vigorous PA for youth, 150–300 min per week for adults, and minimizing SB across all ages, are perfectly suited to support optimal bone health outcomes [45]. Importantly, PA does not necessarily need to be accumulated in bouts of 10 min or more to be effective; rather, even short periods of movement, such as a few minutes at a time, can contribute to meaningful health benefits. Encouraging the mindset of "when you have a minute, take a minute" may help reduce barriers to movement and reinforce the value of incorporating brief, frequent activity into daily routines. A coordinated, multi sectoral effort encompassing healthcare, education, transportation, urban planning, and media sectors is needed to embed a culture of movement into everyday life and to support active living as a foundation for lifelong skeletal health (Table 1)

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Table 1 *Key policy and clinical implications regarding sedentary behavior and physical activity for bone health*

Domain	Key Insight	Clinical Implication	Policy/Public Health Implication
Children & Adolescents	SB is negatively associated with bone density at weight-bearing sites; PA, especially impact-loading activities, enhances bone accrual	Encourage regular participation in pre-school, school and community-based (e.g., organized sports) weight-bearing activities. Screen for high SB and advise on screen time limits	Implement mandatory daily PA in schools; regulate SB and screen time exposure; promote outdoor and sports-based activities; public campaigns highlighting importance of *building* bone mass and benefits of PA
Adults	Moderate-to-vigorous PA maintains or improves BMD, while prolonged SB correlates with lower BMD	Prescribe PA (including resistance and weight-bearing training) as a preventive strategy during clinical visits. Advise on strategies to reduce SB at home and in the workplace. Support PA plan formation through coaching	Promote workplace wellness programs (e.g., standing desks, movement breaks); provide accessible community/gym-based exercise programs; public campaigns highlighting importance of *maintaining* bone health and benefits of PA
(Frail) Older Adults	Both light and vigorous PA benefit bone health: light PA (e.g., walking, household tasks) improves BMD and reduces fracture risk, while more vigorous and resistance-based PA provides even stronger skeletal benefits. SB worsens outcomes, especially in frail individuals	Encourage progressive PA, including supervised resistance and moderate-to-vigorous exercise where appropriate. Routinely assess and counsel on reducing SB and enhancing activity intensity. Support PA plan formation through coaching	Create age-friendly environments encouraging movement (e.g., walkable communities, senior activity centers); ensure accessibility of exercise opportunities for older adults in communities and healthcare settings; public campaigns highlighting importance of reducing bone loss and benefits of PA
Across the Lifespan	PA and SB exert independent effects on bone health; substitution of SB with PA, even light PA, has measurable skeletal benefits	Educate patients on both PA promotion and SB reduction as complementary strategies; assess movement behaviors systematically	Integrate PA and SB targets into (inter)national bone health strategies; ensure alignment with WHO recommendations
Health Inequities & Environment	Urbanization and digital lifestyles contribute to low PA/high SB	Tailor clinical advice to account for environmental and socioeconomic barriers to activity	Address social determinants of health via urban planning (e.g., green spaces, active transport infrastructure) and equitable access to PA opportunities

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