Review

Is running good for bone health?

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Citation: Jamšek B, Vauhnik R. Is running good for bone health? Proceedings of Socratic Lectures, **2026,** 14, 29-38. https://doi.org/10.55295/PSL.14.2026.II6

Abstract:
Running is a widely practiced and accessible form of physical activity with well-established health benefits; however, its effects on bone health remain unclear. This narrative review examines key mechanical, systemic, and individual factors influencing bone adaptation in runners. Current evidence suggests that running may provide some skeletal benefit compared with inactivity, particularly at directly loaded sites such as the lower limb. However, bone responds most effectively to dynamic, high-magnitude, high-rate, and multidirectional loading, whereas the repetitive and high-volume nature of distance running may provide a less potent osteogenic stimulus. Mechanosensory saturation may further limit the effectiveness of prolonged repetitive loading. Beyond mechanical factors, bone health in runners is influenced by systemic factors such as energy availability, hormonal status and sleep, as well as individual factors including training history, early sport specialization, and prior bone stress injuries. Collectively, these findings suggest that running alone may not be sufficient to optimize bone health. Incorporating varied, higher-impact loading alongside running, while addressing systemic and individual determinants, may provide a more effective strategy for maintaining and improving skeletal health. In this review. The aim of this narrative review is to examine some key factors that influence bone adaptation in runners and to discuss their role in long-term bone health.

Keywords: Distance running; Bone health; Bone mineral density; Osteogenic loading; Low energy availability; Bone stress injury

1. Introduction

Running is one of the most popular and accessible forms of physical activity worldwide (Scheerder et al., 2015) and has become increasingly popular over the last 50 years (Vitti et al., 2020). Considering physical inactivity is one of the most significant global health burdens (Katzmarzyk et al., 2022) running is one of the most important forms of physical activity for maintaining and improving health (Hespanhol Junior et al., 2015). Running is also embraced for a variety of reasons including competition, recreation, and social engagement (Shipway & Holloway, 2016). Due to its broad health benefits running is therefore recommended and should be promoted publicly to support policies that support running programs and its benefits (Hespanhol Junior et al., 2015).

Despite the health benefits, running is not free from adverse events. Running-related musculoskeletal injuries are very common among novice and experienced runners (Kakouris et al., 2021). Runners have a 2.5-fold higher injury incidence than individuals in other sports, which shows that running is a "risky" sport, especially considering overuse injuries (Kemler et al., 2018). Some running related overuse injuries are also bone stress injuries (BSI). Although not common in the general population, BSI may account for up to 20 % of all injuries in athletes and military recruits who participate in activities such as marching, running, jumping and dancing (Bennell et al., 1996; Kelly et al., 2024; Milgrom et al., 1985; Rizzone et al., 2017). BSI are a result of repetitive mechanical loading and exist along a pathology continuum beginning with stress reaction and can progress to stress fracture or complete fracture (Warden et al., 2014). Given the relatively high incidence of bone stress injuries in runners, bone health (commonly measured via BMD; Nattiv et al., 2007; Shuhart et al., 2019) emerges as one of key factors influencing both injury risk and adaptation to mechanical loading (Warden et al., 2021a).

Although the mechanical role of bone is to resist external forces, repetitive loading, which is below the complete fracture threshold, results in microdamage formation (Hoenig et al., 2022; Warden et al., 2014). Microdamage is a normal and necessary phenomenon occurring in all skeletons independent from athletic ability (Warden et al., 2021a). Microdamage enables energy dissipation and is a stimulus for targeted remodelling, which involves activation of remodelling units, consisting of an advancing front of bone-resorbing osteoclasts followed by rows of bone-forming osteoblasts (Burr, 2002; Warden et al., 2014). These mechanisms highlight that bone adaptation to repetitive loading is not inherently beneficial but rather depends on the balance between damage accumulation and repair processes (Warden et al., 2021a). While bone stress injuries represent the extreme end of maladaptation, more subtle alterations in bone structure and density may also occur without clinical symptoms. Although, running is likely more beneficial for bone health than doing nothing, the osteogenic potential of running remains unclear, as its effects on bone health likely depend on a complex interaction of mechanical, systemic, and individual factors.

Therefore, the aim of this narrative review is to examine some key factors that influence bone adaptation in runners and to discuss their role in long-term bone health.

2. Methods

This review is based on a descriptive overview of existing scientific literature previously identified and collected in the field of bone tissue adaptation and bone health in runners. Original and review articles were included and further supplemented through screening of reference lists of relevant publications. The aim of this review was not to provide a comprehensive or reproducible search strategy, but rather to present and interpret current evidence relevant to bone tissue adaptation in runners and associations with bone health. The search was limited to articles published in English and in peer-reviewed journals. The identified studies were subsequently organized into thematic sections based on their content. Artificial intelligence-assisted image generation (ChatGPT, OpenAI) was used to create conceptual figure based on author-written manuscript content.

3. Bone adaptations and running: mechanisms and modifying factors

The phenomenon that mechanical loads can affect bone architecture in living beings was first described by Wolff's Law (Frost, 2004). Bone formation, remodelling and damage accumulation processes are stimulated by mechanical strain. More precisely, bone cells are responsive to local mechanical strain expressed in their precise vicinity by routine stresses supplied by activities of daily living. Therefore, the determinants of bone adaptation in response to mechanical loading involve all aspects of the strain environment, including strain magnitude, strain rate, strain frequency, strain distribution, number of loading cycles and rest-recovery periods. All of these components are interlinked and interdependent and together contribute to possible osteogenic effect and potency of mechanical loading (Hart et al., 2017), however some derivatives of strain magnitude are not as relevant to the topic and are outside of scope of this review.

3.1. Mechanical loading characteristics and bone adaptation

Magnitude of strain is key for bone adaptative responses (Hart et al., 2017). Based on "mechanostat theory" different magnitudes of strain continuum elicit bone resorptive, regenerative or formative responses (Frost, 2004). Bone adapts to magnitudes that are above its minimum effective strain thresholds (Ehrlich & Lanyon, 2002; Frost, 2004). It is important to note that based on current understanding, muscle exerts contractile forces onto the skeleton to effectuate movement, providing bone with its largest voluntary delivery of stimulus; superseding gravitational load, e.g. ground reaction forces (DiGirolamo et al., 2013; Hart et al., 2017; Ireland et al., 2014). Furthermore, if indeed maximal strains govern bone adaptations and internal muscle forces are the dominant effectors of bone strain, then maximal muscle force should determine the osteogenic potential of an exercise modality (Ireland et al., 2014). This association of high peak force with bone adaptation is also demonstrated in running athletes of different disciplines (e.g. race walking, long and middle distance running and sprinting) where tibial bone strength is positively associated with the speed of the event and hence the magnitude of ground and presumably internal muscular forces (Ikedo et al., 2016; Wilks et al., 2009).

Strain rate refers to the speed at which strain is applied. Strain rate has been shown to be a critical driver of osteogenesis independent of strain magnitude (Hart et al., 2017). Rapidly applied dynamic loads are more effective in stimulating bone formation compared to slowly applied loads, highlighting the importance of high-rate loading in osteogenic exercise (Hart et al., 2017). In addition, strain location direction and gradient also influence the osteogenic stimulus, with irregular and unusual distribution (spatial delivery) of strain further enhancing bone formation (Gross et al., 1997; Robling et al., 2006). Thus mechanosensitive machinery in bone responds best to high-magnitude loads introduced at high rates (Warden et al., 2021b).

Bone adaptation to loading is site specific (Tenforde & Fredericson, 2011; Warden et al., 2021b) and also exhibits directionality, with bone mass being added and structural geometry developing in accordance with the direction of applied load (Warden et al., 2020). Thus, weight-bearing activities incorporating impulsive loading, particularly those involving some degree of intermittent, explosive jumping and/or sprinting with rapid changes of direction, have the greatest osteogenic potential (Wardenmet al., 2021a). This does not mean that distance running is without skeletal benefit. Cross-sectional evidence suggests that distance runners often demonstrate equal or slightly greater BMD than inactive controls, particularly at directly loaded sites such as the leg or calcaneus (Garofolini & Taylor, 2019), although benefits are less consistent at the lumbar spine or total body (Herbert et al., 2021; Scofield & Hecht, 2012). A review by Scofield and Hecht similarly concluded that running is generally associated with equivalent or slightly higher BMD than inactive controls, but lower BMD than higher-impact sports (Scofield & Hecht, 2012). Therefore, running may be better than inactivity for bone health, but its osteogenic effects appear site-specific and suboptimal compared with more varied loading.

Furthermore, findings presented above are in line with a review by Tenforde & Fredericson (2011) who evaluated differences in bone health caused by sports participation. Athletes who participated in high-impact and multidirectional loading sports, including soccer and basketball, consistently had greater bone mineral density (BMD) and enhanced bone geometric properties compared with those who participated in distance running. In a cross-sectional study of males, soccer players had greater BMD at all sites including the

lumbar spine, femur, calcaneus compared with distance runners and sedentary controls (Fredericson et al., 2007). Additionally, Milgrom et al. (2000) performed in vivo tibia bone strain measurements during simulated activities unique to different sports (basketball and running) and found 50%-100% greater compression and shear strains and greater strain rates during rebound jumping compared with running. These results suggest that greater bone loading forces in basketball may stimulate bone remodelling and result in stiffer more fracture-resistant bones (Tenforde et al., 2015). Also running primarily occurs in a sagittal plane, whereas ball sports incorporate greater multidirectional movements and therefore may result in a more generalized strengthening of bone (Tenforde et al., 2015).
Collectively, these findings indicate that bone adapts most effectively to dynamic, high-magnitude, high-rate, and multidirectional loading, suggesting that repetitive, uniform activities such as distance running may be suboptimal for bone health.

3.2. Loading volume and mechanosensitivity

Strain volume is often aggregately quantified into a total number of loading cycles (Hart et al., 2017). While many combinations of strain magnitude, rate and frequency can interact to provide potent osteogenic stimuli, bone adaptation does not linearly respond to strain volume (Ozcivici et al., 2010; Qin et al., 1998), since skeletal loading duration do not elicit proportional changes in bone mass formation. Rather bone responsiveness to mechanical load eventually declines, highlighting an evident suppression of mechanosensitivity also known as mechanosensory saturation (Burr, 2002; Robling & Turner, 2009). Bone cells are thus responsive to mechanical stimuli in the short term, but their sensitivity to the stimulus wanes quickly after its initiation (Robling & Turner, 2009). Specifically, ~95 % of bone mechanosensitivity is dampened after only 20 to 40 loading cycles at physiologic thresholds, with no benefit of adding beyond 100 loading cycles with equivalent strain loading (Burr et al., 2002; Umemura et al., 1997). In simpler terms, bone cells become "deaf" to repetitive loading; implication being that after running a few minutes, bone cells find the monotonous, unidirectional loading to be boring and they stop responding (Warden et al., 2021a). Nevertheless, subsequent restoration of mechanosensitivity is crucial for effectiveness of future loading. Over 90 % of mechanosensitivity is restored with 4-8 hours of rest between repeat loading bouts (Burr et al., 2002; Robling et al., 2001). These findings confirm the need for the bone stimulus to be short, dynamic, variable which is not the case in distance running. Thus, a few minutes of a bone-centric exercise (e.g. plyometrics) later in the day after a running session may generate further bone adaptation over and above that generated solely by running (Warden et al., 2021a). The addition of bone-centric exercise requires consideration of cumulative bone loads, however approach was used to improve bone health in other endurance sports, such as cycling and swimming (Vlachopoulos et al., 2018b, 2018a).
These mechanisms suggest that high-volume, repetitive loading such as running may not provide a sufficiently effective osteogenic stimulus, since bone responds more favourably to short, dynamic and variable loading, particularly when loading bouts are separated by sufficient rest periods, which helps restore mechanosensitivity.

4. Beyond mechanical loading: systemic factors affecting runner's bone health

Mechanical loading alone does not determine bone adaptation; the skeletal response also depends on whether the athlete has sufficient systemic capacity to support bone formation and remodelling. Poor bone health is common among distance runners. For instance, up to 40 % of female adolescent cross-country runners have a dual-energy X-ray absorptiometry (DEXA) z-score of below -1 for total body or spine areal BMD (Barrack et al., 2008). There are numerous possible reasons for the inferior bone health in cross-country athletes (Hoenig et al., 2022). The most obvious is the high prevalence of low energy availability (LEA) and subsequent relative energy deficiency in sport (REDs), which replaced female athlete triad as a more comprehensive, broader term for the overall syndrome (Mountjoy et al., 2014). Up to 50 % of female runners meet the criteria for disordered eating and/or report menstrual dysfunction (Barrack et al., 2008; Dambacher et al., 2025; Rauh et al., 2020; Skorseth et al., 2020), all of which are detrimental to bone health (Mountjoy et al., 2023).

However, gymnast exhibit higher bone mass than runners despite both populations having a similar prevalence of menstrual dysfunction (Robinson et al., 1995), which might imply that running is just not a good bone-building activity (Warden et al., 2021a).
Although running itself is not the direct cause of LEA it is linked to possible societal norms, perceptions of a need for leanness, sport specific body type, dissatisfaction with body image etc. which could predispose runners to disordered eating behaviours and consequently to LEA (de Borja et al., 2021; Mancine et al., 2020). Even though a lot of the publications study female athletes, detrimental effects of REDs are similar in male athletes, although magnitude of the effects on some physiological parameters and the threshold at which these effects manifest appear to be variable between genders (Mountjoy et al., 2023). Recently, international Delphi consensus listed risk factors for development of BSI (Hoenig et al., 2025) of which a lot of those that reached consensus agreement could be associated with athlete's diet and nutritional demands. When encountering athletes with proximal or central trabecular high-risk BSIs (femoral neck, sacrum, lumbar spine), which are linked to underlying poor bone health (i.e. lower BMD; Ackerman et al., 2015; Tenforde et al., 2018), clinicians should raise suspicion about athletes bone health and possible impact of systemic factors e.g. LEA and hormonal dysfunction (Tenforde et al., 2018, 2024). This just goes to show sufficient energy intake is crucial to maintain and improve runners bone health, whether in a context of pathology or health continuum.
Another important factor when considering runner's bone and systemic health is sleep (Swanson et al., 2018). Disruption or lack of sleep impairs bone formation in otherwise healthy men (Swanson et al., 2017). Also, higher proportion of women with a history of high-risk BSI reported averaging less than 7 hours of sleep a night during the week compared with those with no previous BSI (Tenforde et al., 2024). This is consistent with military data, which showed that a combination of reduced military marching and increase in sleep duration, from 3-4 hours to a minimum of 6 hours, reduced BSI rate in military training by 62 % along with 0.5 % gain in bone mass (Finestone & Milgrom, 2008). These findings suggest that adequate sleep is essential in promoting overall skeletal adaptation.
Collectively, recognizing that bone health is not solely influenced by mechanical load parameters, but also by systemic factors such as energy availability, hormonal function, and sleep, is essential for guiding strategies and promote healthy running culture and associated behaviours to maintain and improve bone health in this high energy expenditure sport.

5. Individual factors and lifespan loading history

In addition to systemic factors, bone health in runners is also shaped by individual loading history across the lifespan. A history of playing multidirectional sport in female runners is associated with better bone health (Warden et al., 2022). This is supported by findings in military recruits who played ball sports for at least two years prior to basic military training and reported 46 % - 84 % reduction in stress fractures compared to recruits who did not play ball sports (Milgrom et al., 2000). It is also important to consider history of bone loading during growth, since it provides once in a lifetime opportunity to optimize bone size (Warden et al., 2021a). Loading in youth encourages additional bone to be added periosteally to further increase bone size (Bass et al., 2002) which exponentially increases bone strength and fatigue resistance for the amount of material added (Warden et al., 2005). This just underpins the importance of higher magnitude, high-rate, multidirectional loading in younger athletes. In contrast, early sport specialization, specifically early distance running specializers had five times the odds (OR = 5.42) of having low BMD (z score < –1.0) compared to low sport specializers (Rauh et al., 2020). Authors elaborate that results may be explained by a complex relationship of multiple interactions of sport exposure with associated behaviours and menstrual dysfunction contributing to low BMD, since they also found high prevalence of LEA and menstrual dysfunction. There is lack of running specific data on early sport specialization in relation to bone health. However, some studies show that early running specializers are at increased risk of overuse injuries (Bell et al., 2018; Pasulka et al., 2017), thus current recommendations are that single sport specialization should be delayed until at least 14 years of age (Sugimoto et al., 2024), so to develop a robust skeleton that can withstand multidirectional loading (Warden et al., 2021a). In addition to youth and developmental factors, bone health considerations are also relevant in master runners, i.e. runners 35 years and older, who present a specific population and thus require nuanced consideration regarding runner's bone health. Nevertheless, similar to younger runners, health considerations in master runners include the goal to optimize bone health with focus on mitigating age-associated loss of bone strength and preventing BSIs (Raiser et al., 2024).

A history of injury, particularly BSI, is another important factor when considering runner's bone health. This is especially relevant for several reasons. Firstly, runners with a history of BSI are at high risk (OR = 4.99) for another BSI (Wright et al., 2015). Secondly, bone remodelling times are long, since it takes 3-6 months for volumetric BMD to return to baseline after a BSI (Popp et al., 2021). However, return to sport may happen sooner (Hoenig et al., 2023), potentially creating a mismatch between tissue recovery and perceived readiness, which is often guided by pain resolution (Popp et al., 2021). Finally, as mentioned before, BSIs are highly prevalent among runners (Rizzone et al., 2017). Collectively, these factors necessitate gradual and well-structured return to running approach that considers multifactorial nature of BSI and prioritizes the protection of long-term skeletal health (Hoenig et al., 2025).

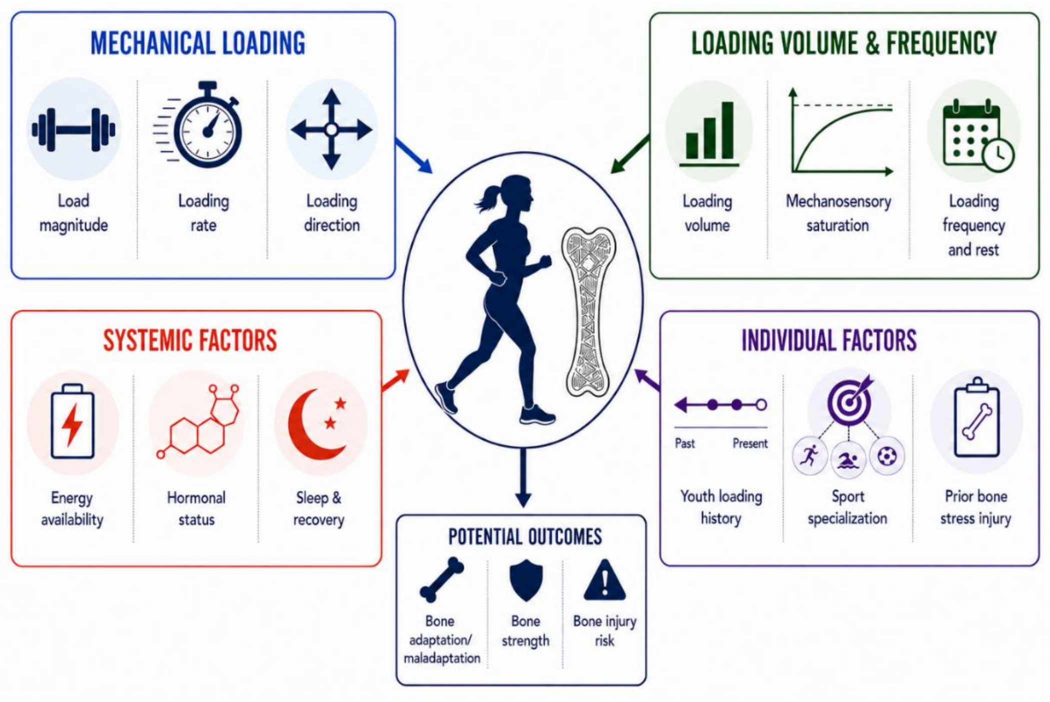

Figure 1. Factors associated with bone health in runners discussed in this review. Figure does mention exhaustive list of all possible factors that could be associated with runner's bone health. The figure was generated using ChatGPT (OpenAI) based on the content of the manuscript.

These findings highlight that bone health in runners is strongly influenced by training history across the lifespan, with early exposure to high-impact, multidirectional loading providing long-term benefits, while early specialization in distance running and prior injury may predispose to suboptimal skeletal outcomes, emphasizing the need for a lifespan and multimodal approach to optimizing bone health.

6. Limitations and future directions

Our narrative review presented arguments regarding the circumstances in which running may be beneficial or detrimental to skeletal health. We included a lot of cross-sectional and observational studies which allows for hypothesis generation but does not enable to establish causal relationships between running related factors and bone health outcomes. In addition, some findings are extrapolated from non-running populations, which may limit their applicability to runners. Finally, there is a relative lack of running-specific studies, which would capture the multiple factors in a prospective study design to really elucidate the magnitude of the effect of certain factors associated with runner's long term bone health. This highlights the need for further research in this area.

7. Conclusions

Running is a widely accessible and beneficial form of physical activity and may provide some skeletal benefit compared with inactivity, particularly at directly loaded sites such as the lower limb. However, its effectiveness as a standalone osteogenic stimulus appears limited compared to other loading variations. Bone adapts most effectively to dynamic, high-magnitude, high-rate, and multidirectional loading, whereas the repetitive and high-volume nature of distance running may provide a less potent stimulus for improving whole-skeleton bone health. In addition, bone health in runners is influenced by systemic factors such as energy availability, hormonal status and sleep, as well as individual factors including training history, early sport specialization, and prior injury. Therefore, running alone may not be sufficient to optimize bone health. Incorporating varied, higher-impact loading alongside running, while addressing systemic and individual factors, may provide a more effective strategy for maintaining and improving skeletal health.

Funding: : The authors acknowledge the financial support from the Slovenian Research Agency (research core funding no. P3-0388.

Conflicts of Interest: The authors declare no conflict of interest.

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