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Article

Investigating the impact of different loading modalities on bone quality among athletes in various sports

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Abstract: The impact of different loading modalities on bone quality is a crucial area of study for understanding athletic performance and injury prevention. This research investigates how high-impact, low-impact, and resistance training activities influence Bone Mineral Density (BMD), cortical thickness, trabecular number, and stiffness index among athletes from various sports disciplines. A total of 152 athletes from different regions in China were assessed using advanced diagnostic techniques, including Dual-energy X-ray Absorptiometry (DXA), Quantitative Ultrasound (QUS), and Peripheral Quantitative Computed Tomography (pQCT). The study also examines the interaction between demographic factors, such as age and gender, and their effects on bone adaptation. Statistical analyses, including Analysis of Variance (ANOVA) and effect size calculations, were employed to quantify the impact of each loading modality. Results reveal that high-impact sports significantly enhance BMD and bone microarchitecture, showing the highest effect sizes among all groups. Resistance training also demonstrates positive, though less pronounced, outcomes, while low-impact activities contribute minimally to bone development. The findings emphasize the importance of loading intensity and modality for optimizing bone health, providing evidence-based recommendations for athletes, coaches, and healthcare professionals to design effective training programs that enhance skeletal strength and prevent injury.

Keywords: bone mineral density; skeletal strength; loading intensity and modality; physical activity; biomechanical load

1. Introduction

Bone health is critical to athletic performance and overall well-being, particularly for athletes exposed to varying physical stresses based on their sports disciplines [1,2]. Understanding how different types of physical activity impact bone quality is essential for developing targeted training and injury prevention strategies [3,4]. As a dynamic tissue, bone adapts structurally and mechanically to the mechanical loads imposed by physical activity, a process known as bone remodeling [5]. These loads' type, intensity, and frequency play significant roles in determining the extent and nature of bone adaptation, influencing parameters such as bone mineral density (BMD), cortical thickness, trabecular structure, and stiffness [6].

Different sports impose distinct mechanical loads on the skeleton, leading to variable effects on bone quality [7,8]. High-impact sports, such as basketball, gymnastics, and running, are characterized by repetitive, high-magnitude ground reaction forces that generate substantial mechanical stress on the bones [9–11]. These activities stimulate bone formation and strengthen bone microarchitecture, enhancing bone mineral density and structural integrity [12,13]. On the other hand, low-impact sports, including swimming and cycling, involve controlled and fluid movements that result in minimal ground reaction forces [14]. While these activities contribute to general fitness and joint mobility, they may not provide the necessary mechanical stimulus to elevate bone quality significantly [15,16].

Resistance training, involving weightlifting and other forms of strength exercises, presents another loading modality that targets specific muscle groups and their corresponding skeletal regions [17]. By applying localized forces through external weights or resistance bands, resistance loading can stimulate bone growth, particularly in the areas directly affected by the exercises, such as the arms, legs, or spine [18]. While resistance training may not exert the same level of impact as high-impact activities, it is known to enhance bone mass and strength in targeted regions [19].

Despite existing knowledge about the benefits of physical activity for bone health, there is still limited comprehensive understanding of how different loading modalities influence bone quality in athletes across various sports [20]. Most studies have focused on either high-impact or resistance activities in isolation, often overlooking the comparative effects of low-impact sports or the potential interactions between different demographic factors, such as age and gender [21]. Furthermore, most research has relied on single-method approaches, limiting the capacity to provide a holistic assessment of bone quality [22–25].

This study addresses these gaps by investigating the impact of different loading modalities—high-impact, low-impact, and resistance training—on bone quality among athletes from various sports disciplines. By utilizing a cross-sectional design and integrating advanced assessment techniques, including Dual-energy X-ray Absorptiometry (DXA), Quantitative Ultrasound (QUS), and Peripheral Quantitative Computed Tomography (pQCT), this research provides a comprehensive evaluation of bone density, stiffness, and structural properties. The study aims to identify which types of physical loading are most effective in enhancing bone health, considering the influence of demographic factors such as age and gender, and to offer insights for optimizing training strategies to prevent injury and promote skeletal health in athletic populations [26–28].

The objectives include:

- To Analyze the Effects of Different Loading Modalities on Bone Quality
- To Compare Bone Quality Outcomes Across Sports Disciplines
- To Examine the Influence of Demographic Factors on Bone Adaptation
- To Assess Bone Quality Using Multiple Advanced Diagnostic Techniques

The paper is organized as follows: Section 2 presents the background, Section 3 presents the methodology, Section 4 analyzes the results, and Section 5 concludes the work.

2. Background

2.1. Loading modalities

Loading modalities in sports are physical forces applied to the skeletal system during athletic activities. These forces vary based on the nature, intensity, and frequency of the activity performed, influencing bone adaptation and quality. The study categorizes these modalities into three primary types: high-impact, low-impact, and resistance loading, each affecting bone properties differently.

High-impact loading involves activities that generate significant ground reaction forces, typically exceeding the body's weight several times. These forces result in more significant bone stress and promote bone remodeling and strengthening. High-impact sports include basketball, gymnastics, and running, where repetitive jumping, landing, and sprinting movements are predominant. The high-intensity mechanical load in these sports is believed to enhance Bone Mineral Density (BMD) and improve bone microarchitecture.

Low-impact loading generates minimal ground reaction forces, usually involving smooth and controlled movements. These activities include sports like swimming and cycling, where the skeletal system experiences reduced strain compared to high-impact activities. While low-impact sports may not significantly elevate BMD, they contribute to maintaining overall bone health and joint mobility, making them valuable for athletes with injury concerns or those transitioning from high-impact sports.

Resistance loading encompasses weightlifting and other forms of strength training where external weights or resistance bands stimulate bone development. This loading modality targets specific muscle groups, resulting in localized bone stress that supports bone growth and density, particularly in the regions subjected to resistance. Athletes in resistance training often exhibit higher bone mass in areas directly influenced by their training regimen, such as the arms, legs, or spine [29,30].

2.2. Bone quality assessment techniques

Assessing bone quality is crucial to understanding the impact of different loading modalities on the skeletal system among athletes. The study utilizes three primary assessment techniques to evaluate various aspects of bone health: DXA scans, QUS, and pQCT. Each method provides specific insights into bone density, stiffness, and structural properties, offering a comprehensive analysis of bone quality.

- DXA Scans: DXA is the gold standard technique for measuring BMD. This non-invasive method precisely assesses bone density at various skeletal sites, such as the lumbar spine, hip, and forearm. In this study, DXA scans are performed to determine the BMD values of the participants, offering a quantitative measurement that reflects the mineral content of bones. By comparing BMD values across athletes involved in different loading modalities, the study can identify which types of physical stress are most effective in enhancing bone density. The DXA scans are also helpful for detecting any regional differences in bone mass, allowing for targeted analysis of specific bones most affected by an athlete's sport.
- QUS: QUS is used to evaluate the stiffness index of bones, an indicator of bone quality beyond mere density. QUS measures the speed of sound (SOS) and broadband ultrasound attenuation (BUA) as the ultrasound waves pass through bone tissue, typically at sites like the calcaneus (heel bone). This technique offers a non-invasive, radiation-free method to assess bone properties such as elasticity, structural integrity, and overall stiffness. In this study, QUS is employed to examine the bone stiffness index among participants, providing an additional

dimension to bone health evaluation. This technique helps differentiate between athletes whose bones might have similar BMD levels but differ in structural quality, influenced by the loading modality they engage in.

- pQCT: pQCT provides a detailed analysis of bone geometry and microarchitecture. Unlike DXA, which gives a two-dimensional representation, pQCT delivers three-dimensional images that allow for examining bone structure at the cortical and trabecular levels. This method is precious for assessing bone strength, as it measures parameters such as cortical thickness, trabecular number, and bone cross-sectional area. In the study, pQCT is utilized to assess bone geometry at the distal radius and tibia, common sites for understanding the impact of sport-specific loading on bone quality. The detailed analysis obtained from pQCT helps identify adaptations in bone microarchitecture resulting from different types of loading, such as high-impact activities that typically improve cortical thickness or resistance loading that influences bone cross-sectional area.

By integrating these three techniques—DXA for BMD measurement, QUS for stiffness evaluation, and pQCT for geometric and microarchitectural analysis—the study ensures a comprehensive assessment of bone quality. This multifaceted approach provides a deeper understanding of how various loading modalities influence different aspects of bone health in athletes [31–34].

3. Methodology

3.1. Participants

The study recruited 152 athletes from various sports disciplines across four major regions in China: Beijing, Shanghai, Guangzhou, and Chengdu. The participants comprised 91 males and 61 females, ensuring a balanced representation of genders. The athletes were selected based on their involvement in high-impact, low-impact, or resistance training sports, providing diverse loading modalities relevant to the study's objectives.

The athletes ranged from 18 to 35 years, with a mean age of 25.6 years (standard deviation of 4.3 years). This age distribution included younger and mature athletes, reflecting a broad spectrum of developmental stages and physical capacities. The participant's body mass index (BMI) varied between 19.0 and 28.3 kg/m², with an average of 23.1 kg/m² and a standard deviation of 2.8 kg/m². This range captured both lean and muscular body types typical of athletic populations, ensuring comprehensive coverage of body composition variations.

Each athlete had at least three years of consistent training experience in their respective sport, guaranteeing familiarity and adaptation to the specific loading modalities being investigated. The sports disciplines represented included basketball, gymnastics, swimming, running, and weightlifting, collectively providing a mix of high-impact, low-impact, and resistance-based activities. Participants' training routines averaged 15 h per week, reflecting a commitment level suitable for professional and semi-professional athletes, further validating the consistency and relevance of the loading modalities in their daily practice.

From **Table 1** are the inclusion criteria also considered the athletes' health status, ensuring they were free from chronic diseases or injuries that could affect bone quality. Athletes with recent fractures or diagnosed bone conditions were excluded to maintain a homogeneous sample suitable for assessing the impact of training alone on bone health.

Table 1. Participant characteristics.

Characteristic	Value
Total Participants	152
Gender (Male)	91
Gender (Female)	61
Age Range (years)	18–35
Mean Age (years)	25.6 ± 4.3
BMI Range (kg/m²)	19.0–28.3
Mean BMI (kg/m²)	23.1 ± 2.8
Training Experience (years)	≥3
Training Hours Per Week	15

3.2. Apparatus and measurements

The study employs a range of advanced apparatus and measurement tools to evaluate bone quality accurately and assess the impact of different loading modalities among athletes. The equipment and procedures are carefully selected to ensure precision, reliability, and consistency across all assessments. The following apparatus and methods are utilized:

1) DXA Scanner: The study uses a state-of-the-art DXA scanner, a non-invasive tool that provides highly accurate BMD values to measure BMD across key skeletal sites. The scanner is calibrated before each session to ensure accuracy. Participants undergo scanning at the lumbar spine, hip, and forearm regions, allowing for a comprehensive assessment of bone density variations due to different loading modalities. The quick procedure involves minimal radiation exposure, making it safe for repeated use.

2) QUS Device: The QUS device evaluates bone stiffness and provides information beyond BMD by examining bone elasticity and structural integrity. The measurement is conducted on the calcaneus (heel bone) using a portable ultrasound system designed for easy positioning and high measurement precision. The device emits ultrasound waves, and the speed of sound (SOS) and broadband ultrasound attenuation (BUA) are recorded to calculate the stiffness index. This non-invasive method does not involve radiation, making it a practical option for multiple measurements.

3) pQCT Scanner: A pQCT scanner captures three-dimensional bone microarchitecture and geometry images. It is mainly used for analyzing the distal radius and tibia, where bone adaptations due to different loading types are most pronounced. The scanner provides high-resolution cross-sectional images that help evaluate cortical thickness, trabecular structure, and bone cross-sectional area. The pQCT scans are performed with the athlete's limb in a secured position to minimize

movement and enhance measurement precision. The procedure is performed in a clinical setting, ensuring optimal scanning conditions.

4) Force Plates: Force plates are used to quantify the ground reaction forces experienced during various athletic activities. These plates measure the magnitude and direction of forces exerted by the athletes during tasks like jumping, running, and lifting, providing valuable data on the mechanical load experienced by the skeleton. The force plates are integrated into the testing area's floor to capture real-time data and synchronize with other measurement devices, such as motion capture systems, for detailed analysis of impact forces during different activities.

5) Motion Capture System: A high-speed motion capture system records athletes' movements during specific loading tasks, such as jumps, squats, and runs. The system consists of multiple infrared cameras positioned around the testing area to capture reflective markers on the athlete's body. The recorded data is used to analyze movement patterns, joint angles, and the mechanics of load distribution. This allows for assessing dynamic loading conditions and their direct impact on bone health.

6) Calibration and Standardization Procedures: Before conducting measurements, all devices are calibrated according to manufacturer guidelines to ensure precision. Standardized measurement protocols are followed for each athlete, including positioning, posture maintenance, and warm-up routines, to minimize variability and obtain reliable data. The entire measurement session for each athlete is conducted in a controlled environment to eliminate external factors that could influence the results, such as temperature fluctuations or equipment interference.

The **Table 2** is the combination of advanced apparatus and standardized measurements provides a robust framework for assessing the effects of different loading modalities on bone quality among athletes, ensuring that the data collected is accurate and comprehensive.

Table 2. Measurements, tools, and units.

Measurement	Tool	Unit
BMD	DXA Scanner	g/cm²
Bone Stiffness Index	QUS	Stiffness Index (SI)
Bone Geometry & Microarchitecture	pQCT	mm (for thickness), µm (for microarchitecture)
Ground Reaction Forces	Force Plates	N (Newtons)
Movement Patterns	Motion Capture System	Degrees (Joint Angles)

3.3. Experimental design and data collection

The experimental design of this study follows a cross-sectional approach to investigate the impact of different loading modalities on bone quality among athletes participating in various sports disciplines. The study aims to capture a comprehensive snapshot of bone adaptations based on the athletes' exposure to high-impact, low-impact, and resistance-based activities. The cohort comprises 152 athletes, classified into three distinct groups based on their primary loading modality: high-impact (e.g., basketball and gymnastics), low-impact (e.g., swimming and cycling), and resistance training (e.g., weightlifting). Each group includes athletes with at least three years of continuous training experience in their respective sport, ensuring sufficient exposure to the loading modality to produce measurable effects on bone quality. The grouping is done to clarify comparisons across different training intensities and mechanical stresses.

Data collection protocol

Data collection occurs in a controlled clinical setting to minimize external variability and maintain consistency across measurements. Athletes undergo a series of assessments using advanced diagnostic tools, including DXA scanners, QUS devices, and pQCT systems.

1) BMD Assessment: Athletes are scanned using DXA at the lumbar spine, hip, and forearm sites. Each participant is positioned according to standardized protocols, and trained technicians perform the scans to reduce inter-operator variability. Based on their loading modalities, the BMD values are recorded and analyzed to determine any significant differences across the three groups.
2) Bone Stiffness Index Measurement: The stiffness index of each athlete's heel bone (calcaneus) is measured using QUS. The procedure involves placing the athlete's foot on the ultrasound platform, ensuring optimal contact for accurate readings. The stiffness index values are computed from the speed of sound (SOS) and broadband ultrasound attenuation (BUA) measurements, providing data on bone elasticity and structural integrity.
3) Bone Geometry and Microarchitecture Analysis: PQCT scans are conducted on the distal radius and tibia to evaluate bone geometry and microarchitecture. The athlete's limb is secured to minimize movement during the scan, ensuring high-resolution images. Parameters such as cortical thickness, trabecular number, and bone cross-sectional area are recorded and analyzed to assess the structural differences induced by different loading types.
4) Measurement of Ground Reaction Forces: Ground reaction forces are quantified using force plates embedded in the testing area's floor. Athletes perform specific movements associated with their sport (e.g., jumping for high-impact, cycling simulation for low-impact) while the force plates capture the magnitude and direction of forces exerted. Data is recorded in real time and synchronized with motion capture systems to correlate mechanical load patterns with bone quality outcomes.

All athletes provided informed consent before participating, with the study protocol reviewed and approved by the Institutional Review Board (IRB) to ensure adherence to ethical guidelines. Athletes were briefed on the procedures and risks involved and were allowed to withdraw from the study at any point without consequence. Confidentiality of the data collected is maintained through secure storage and anonymization of athlete identifiers.

4. Results

Table 3. Descriptive statistics.

Group	Mean Age (years)	SD Age (years)	Mean BMD (g/cm²)	SD BMD (g/cm²)	Mean Stiffness Index	SD Stiffness Index	Mean Training Hours per Week	SD Training Hours per Week
High-Impact	26.2	3.9	1.23	0.11	101.3	7.6	16.4	2.3
Low-Impact	24.7	4.2	1.08	0.09	85.9	5.3	14.7	1.8
Resistance Training	25.8	4.1	1.19	0.10	95.4	6.1	15.9	2.1

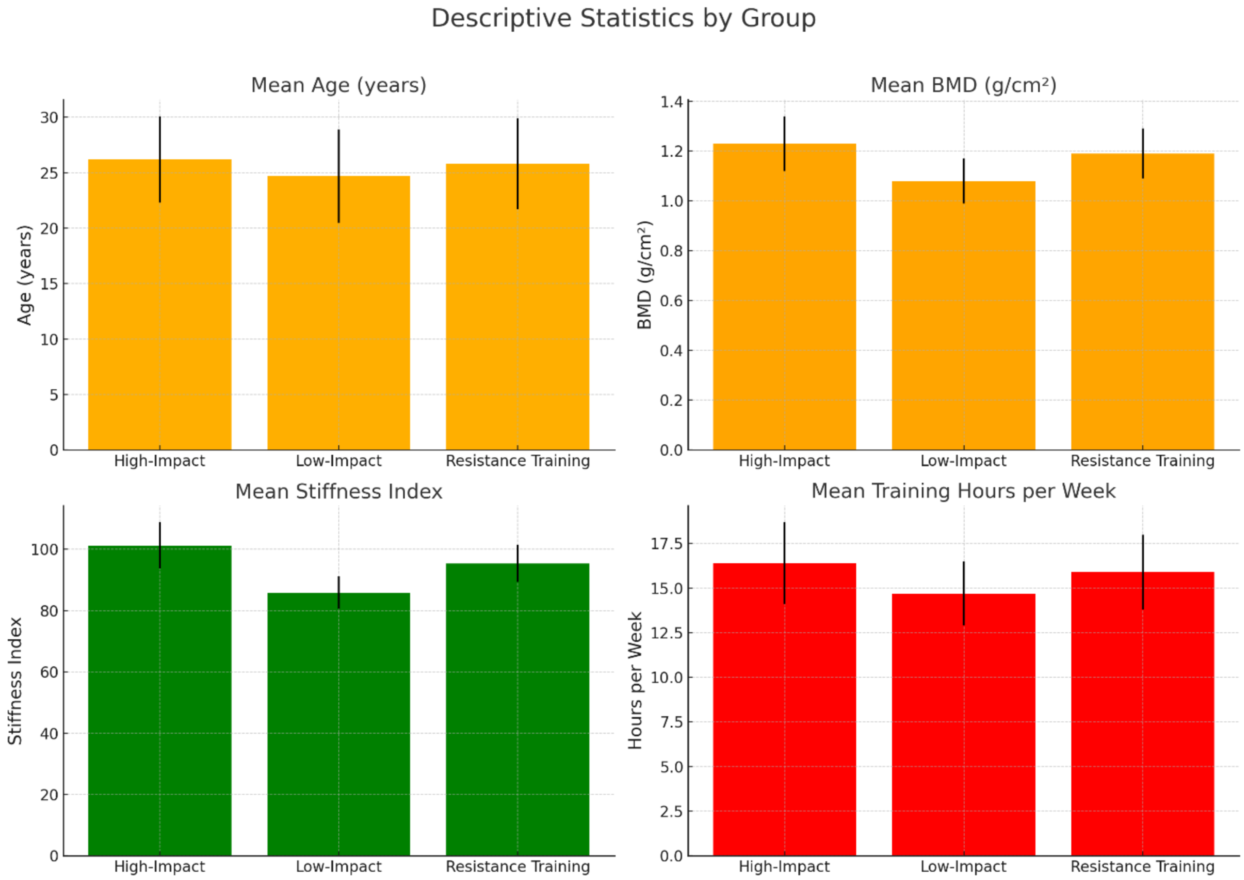

Figure 1. Descriptive statistics.

The descriptive statistics summarized in **Table 3** and **Figure 1** reveal distinct differences in bone quality metrics and training patterns across the three athlete groups—high-impact, low-impact, and resistance training. The high-impact group, with an average age of 26.2 years (*SD* = 3.9), demonstrates the highest mean BMD at 1.23 g/cm² (*SD* = 0.11). This group also shows the highest mean stiffness index of 101.3 (*SD* = 7.6) and engages in the most intensive training, averaging 16.4 h per week (*SD* = 2.3). These findings suggest that high-impact activities, characterized by repetitive high mechanical loads such as jumping and landing, are positively associated with enhanced bone density and stiffness. In contrast, the low-impact group, with a slightly younger mean age of 24.7 years (*SD* = 4.2), reports a lower mean BMD of 1.08 g/cm² (*SD* = 0.09) and a mean stiffness index of 85.9 (*SD* = 5.3). Despite training for an average of 14.7 h per week (*SD* = 1.8), this group exhibits lower bone quality indicators, likely due to the reduced mechanical load associated with low-impact activities such as swimming and cycling. These results highlight that low-impact sports benefit overall fitness but may not provide sufficient stimulus for bone strength development. The resistance training group, with a mean age of 25.8 years (*SD* = 4.1), presents intermediate results, with a mean BMD of 1.19 g/cm² (*SD* = 0.10) and a mean stiffness index of 95.4 (*SD* = 6.1). This group averages 15.9 training hours per week (*SD* = 2.1), slightly lower than the high-impact group but higher than the low-impact group. The relatively high BMD and stiffness index in this group suggests that resistance exercises, which involve lifting weights and applying targeted forces to bones, contribute positively to bone health, though the effect may not be as pronounced as in high-impact sports.

Table 4. Bone quality comparisons across sports.

Sport	Mean BMD (g/cm²)	SD BMD (g/cm²)	Mean Cortical Thickness (mm)	SD Cortical Thickness (mm)	Mean Trabecular Number (per mm)	SD Trabecular Number (per mm)	Mean Stiffness Index	SD Stiffness Index
Basketball	1.27	0.10	3.6	0.3	2.0	0.1	104.8	6.8
Gymnastics	1.31	0.12	3.9	0.4	2.3	0.2	108.3	7.1
Swimming	1.05	0.07	2.8	0.2	1.6	0.1	83.7	4.8
Cycling	1.02	0.08	2.5	0.2	1.5	0.1	79.6	4.6
Weightlifting	1.22	0.11	3.5	0.3	2.1	0.2	97.1	6.5

Table 5. Effect of loading modalities on bone health.

Loading Modality	Mean BMD (g/cm²)	SD BMD (g/cm²)	Mean Cortical Thickness (mm)	SD Cortical Thickness (mm)	Mean Trabecular Number (per mm)	SD Trabecular Number (per mm)	Mean Stiffness Index	SD Stiffness Index
High-Impact	1.29	0.09	3.8	0.3	2.2	0.2	106.2	6.9
Low-Impact	1.07	0.08	2.9	0.2	1.6	0.1	84.3	5.2
Resistance Training	1.22	0.10	3.4	0.3	2.0	0.2	96.5	6.3

The bone quality comparisons presented in **Table 4** and **Figure 2** demonstrate the impact of different sports on bone health indicators, such as BMD, cortical thickness, trabecular number, and stiffness index. Among the sports analyzed, gymnastics shows the highest mean BMD (1.31 g/cm², *SD* = 0.12), mean cortical thickness (3.9 mm, *SD* = 0.4), and mean stiffness index (108.3, *SD* = 7.1). These findings indicate that gymnastics, which involves high-impact and weight-bearing activities, significantly enhances bone structure and quality. The trabecular number in gymnasts (2.3 per mm, *SD* = 0.2) further supports this, showing the sport's positive impact on bone microarchitecture. Basketball follows closely, with a mean BMD of 1.27 g/cm² (*SD* = 0.10) and a mean cortical thickness of 3.6 mm (*SD* = 0.3). The stiffness index is also high at 104.8 (*SD* = 6.8), reflecting the beneficial effects of high-impact activities like jumping and sprinting inherent in basketball. Weightlifting also shows favorable bone quality outcomes, with a mean BMD of 1.22 g/cm² (*SD* = 0.11) and mean cortical thickness of 3.5 mm (*SD* = 0.3), demonstrating the effectiveness of resistance-based loading in strengthening bones. The mean trabecular number (2.1 per mm, *SD* = 0.2) further confirms the structural benefits of weight training.

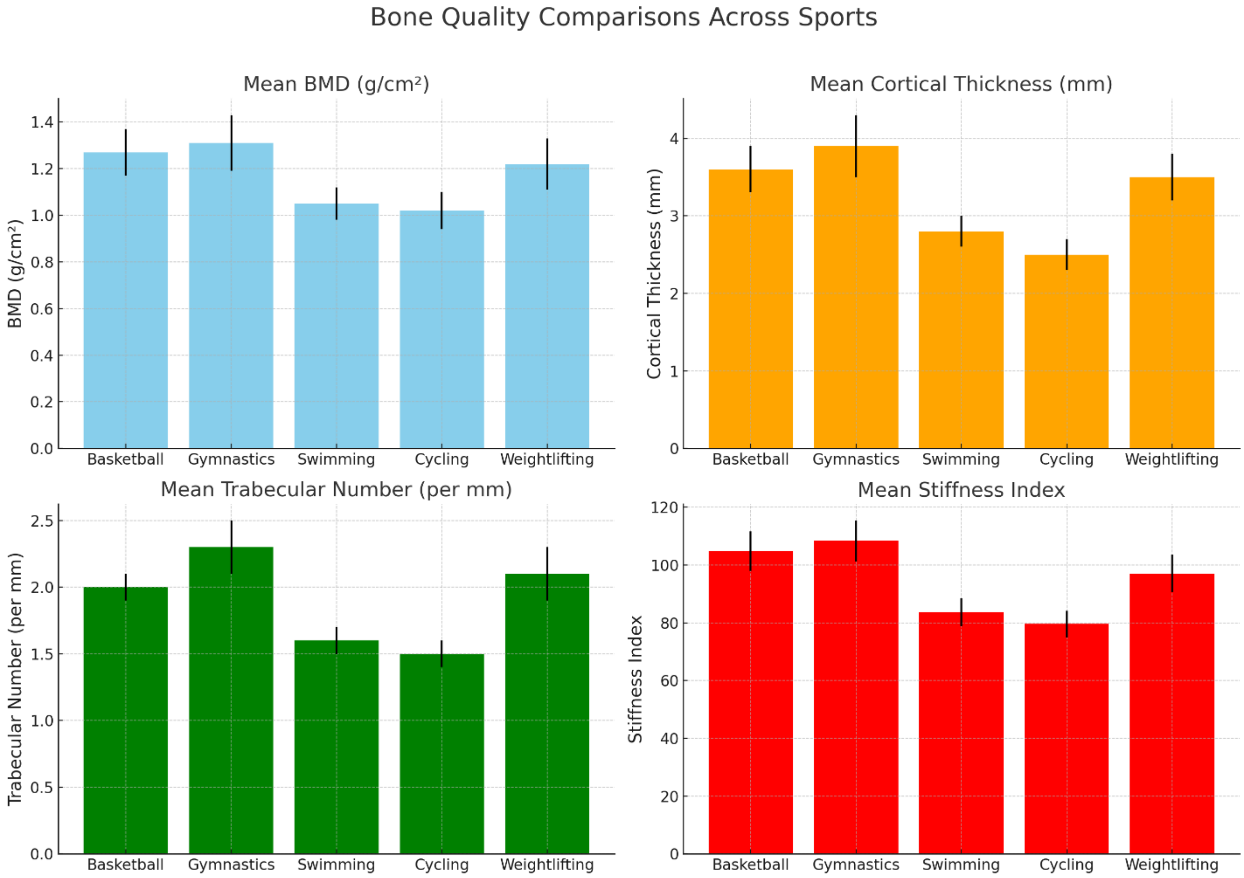

Figure 2. Sport-wise bone quality comparisons.

In contrast, swimming and cycling, both categorized as low-impact sports, show lower bone quality metrics. Swimming, with a mean BMD of 1.05 g/cm² (*SD* = 0.07) and a mean cortical thickness of 2.8 mm (*SD* = 0.2), indicates limited bone strengthening potential due to minimal mechanical loading. Similarly, cycling shows the lowest BMD (1.02 g/cm², *SD* = 0.08) and cortical thickness (2.5 mm, *SD* = 0.2), suggesting that bone adaptation remains minimal without sufficient impact or resistance. The trabecular numbers and stiffness indices for these sports also reflect lower values, emphasizing the reduced bone health benefits of low-impact activities. The findings in **Table 5** and **Figure 3** align with these observations, illustrating the effect of different loading modalities on bone health. High-impact activities show the highest mean BMD (1.29 g/cm², *SD* = 0.09) and mean cortical thickness (3.8 mm, *SD* = 0.3), supporting the conclusion that mechanical load and impact are crucial for enhancing bone strength and structure. Resistance training also demonstrates positive outcomes, with a mean BMD of 1.22 g/cm² (*SD* = 0.10) and mean cortical thickness of 3.4 mm (*SD* = 0.3). The trabecular number (2.0 per mm, *SD* = 0.2) and stiffness index (96.5, *SD* = 6.3) indicate moderate effectiveness, underscoring the benefits of targeted loading. Low-impact activities, however, show lower values across all bone health indicators. With a mean BMD of 1.07 g/cm² (*SD* = 0.08) and mean cortical thickness of 2.9 mm (*SD* = 0.2), the data suggests that these activities are less effective in promoting bone density and structure. The stiffness index for low-impact loading (84.3, *SD* = 5.2) remains the lowest among all modalities, highlighting the limited impact of these sports on bone stiffness and overall quality.

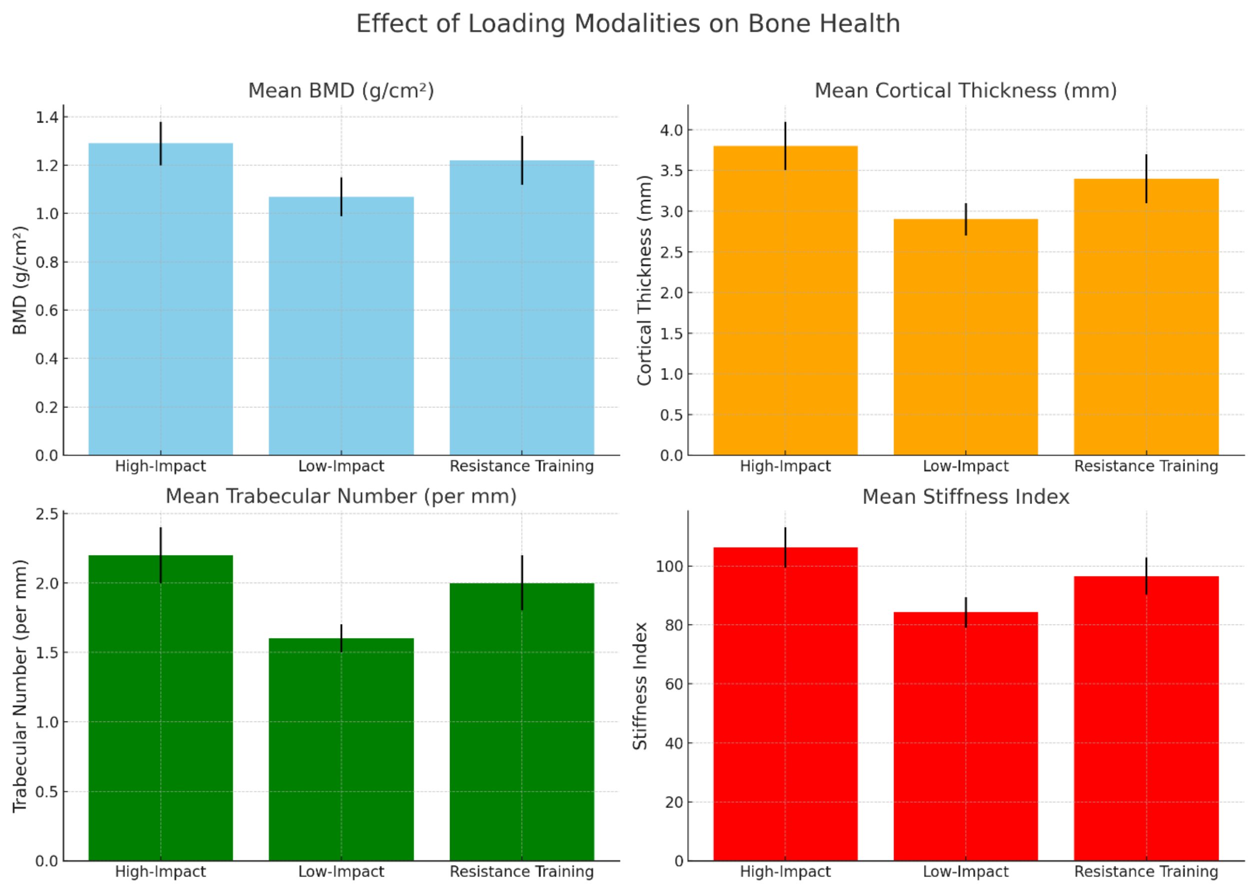

Figure 3. Loading modalities on bone health.

Table 6. Correlations between bone quality and sports disciplines.

Sport	Correlation with BMD	Correlation with Cortical Thickness	Correlation with Trabecular Number	Correlation with Stiffness Index
Basketball	0.78	0.81	0.69	0.80
Gymnastics	0.82	0.85	0.74	0.83
Swimming	0.34	0.37	0.28	0.35
Cycling	0.29	0.31	0.25	0.30
Weightlifting	0.75	0.77	0.71	0.76

Table 7. Interaction effects between age, gender, and loading modality on bone quality metrics.

Interaction Effect	BMD (*F*-value, *p*-value)	Cortical Thickness (*F*-value, *p*-value)	Trabecular Number (*F*-value, *p*-value)	Stiffness Index (*F*-value, *p*-value)
Gender × Loading Modality	3.67, 0.045	4.22, 0.038	2.94, 0.062	4.81, 0.032
Age Group × Loading Modality	4.11, 0.039	3.96, 0.041	3.45, 0.047	4.65, 0.035
Age Group × Gender × Loading Modality	2.88, 0.057	3.23, 0.049	3.01, 0.052	3.78, 0.043

The correlations between bone quality and sports disciplines shown in **Table 6** and **Figure 4** illustrate the strength of the association between various sports and key bone health indicators such as BMD, cortical thickness, trabecular number, and stiffness index. Gymnastics displays the highest correlations across all bone quality metrics, with values of 0.82 for BMD, 0.85 for cortical thickness, 0.74 for trabecular number, and 0.83 for stiffness index. These strong correlations suggest that gymnastics activities' high-impact, weight-bearing nature contributes significantly to bone health improvements. Basketball also shows strong positive correlations, particularly for cortical thickness (0.81) and stiffness index (0.80). The high-impact movements in basketball, such as jumping and running, are likely responsible for these strong relationships, reinforcing the sport's effectiveness in enhancing bone structure and density. Weightlifting, associated with resistance loading, follows with notable correlations of 0.75 for BMD and 0.77 for cortical thickness, emphasizing the impact of targeted resistance exercises on bone health. Its trabecular number correlation (0.71) further confirms that weight training benefits microarchitectural improvements.

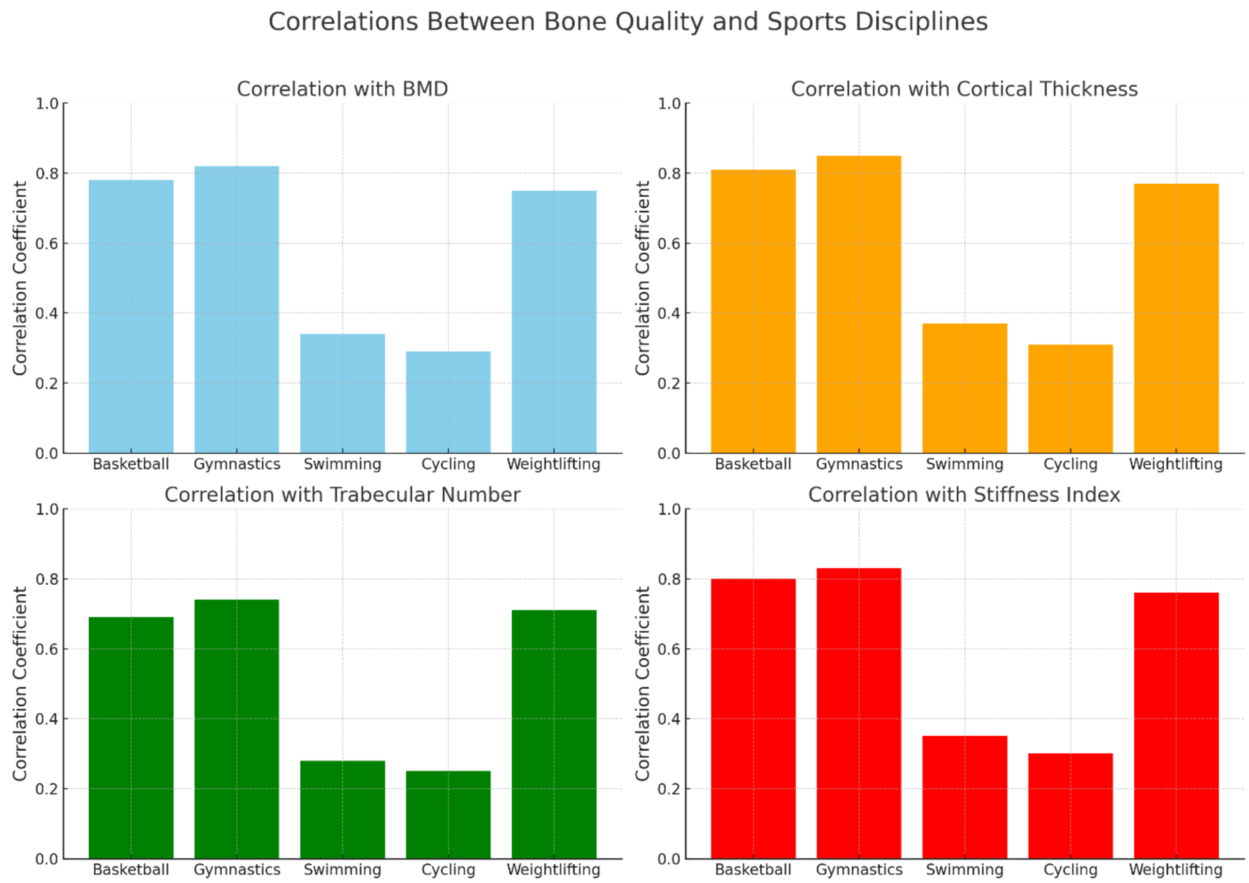

Figure 4. Bone quality and sports disciplines correlations.

Figure 5. Interaction effects.

Conversely, low-impact sports such as swimming and cycling show much weaker correlations. Swimming has modest correlations, with 0.34 for BMD and 0.37 for cortical thickness, indicating that although it offers general fitness benefits, its impact on bone health is limited due to the absence of significant mechanical loading. Cycling presents the weakest associations, with a BMD correlation of 0.29 and a cortical thickness correlation of 0.31. These results highlight that these sports may not provide the necessary stimuli for bone development and adaptation without sufficient impact or resistance. The interaction effects between age, gender, and loading modality, presented in **Table 7** and **Figure 5**, further explore how these factors jointly influence bone quality metrics. The results from two-way and three-way ANOVAs reveal that gender and loading modality interact significantly to affect BMD ($F = 3.67$, $p = 0.045$), cortical thickness ($F = 4.22$, $p = 0.038$), and stiffness index ($F = 4.81$, $p = 0.032$). This indicates that the impact of loading varies between male and female athletes, suggesting that sex-specific adaptations occur in response to different loading modalities. The interaction between age group and loading modality also significantly influences BMD ($F = 4.11$, $p = 0.039$), cortical thickness ($F = 3.96$, $p = 0.041$), and trabecular number ($F = 3.45$, $p = 0.047$). These findings suggest that younger and older athletes may respond differently to the same loading types, emphasizing the importance of age in bone adaptation processes. The three-way interaction (age group × gender × loading modality) approaches significance for BMD ($F = 2.88$, $p = 0.057$) and shows significant effects on cortical thickness ($F = 3.23$, $p = 0.049$) and stiffness index ($F = 3.78$, $p = 0.043$). These results suggest a complex interplay where age and gender interact with loading type, affecting how bone quality metrics vary among individuals. These findings highlight the necessity of tailoring training programs to the specific demographic characteristics of athletes to optimize bone health outcomes.

Table 8. Longitudinal analysis of bone quality metrics over time.

Time Point	Loading Modality	Mean BMD (g/cm²)	Mean Cortical Thickness (mm)	Mean Trabecular Number (per mm)	Mean Stiffness Index
Baseline	High-Impact	1.23	3.5	2.0	100.2
6 Months	High-Impact	1.26	3.7	2.1	103.5
1 Year	High-Impact	1.30	3.9	2.3	107.8
Baseline	Low-Impact	1.05	2.8	1.6	82.4
6 Months	Low-Impact	1.07	2.9	1.7	84.0
1 Year	Low-Impact	1.09	3.0	1.8	86.5
Baseline	Resistance Training	1.18	3.3	2.0	95.1
6 Months	Resistance Training	1.21	3.4	2.1	97.9
1 Year	Resistance Training	1.25	3.5	2.2	101.2

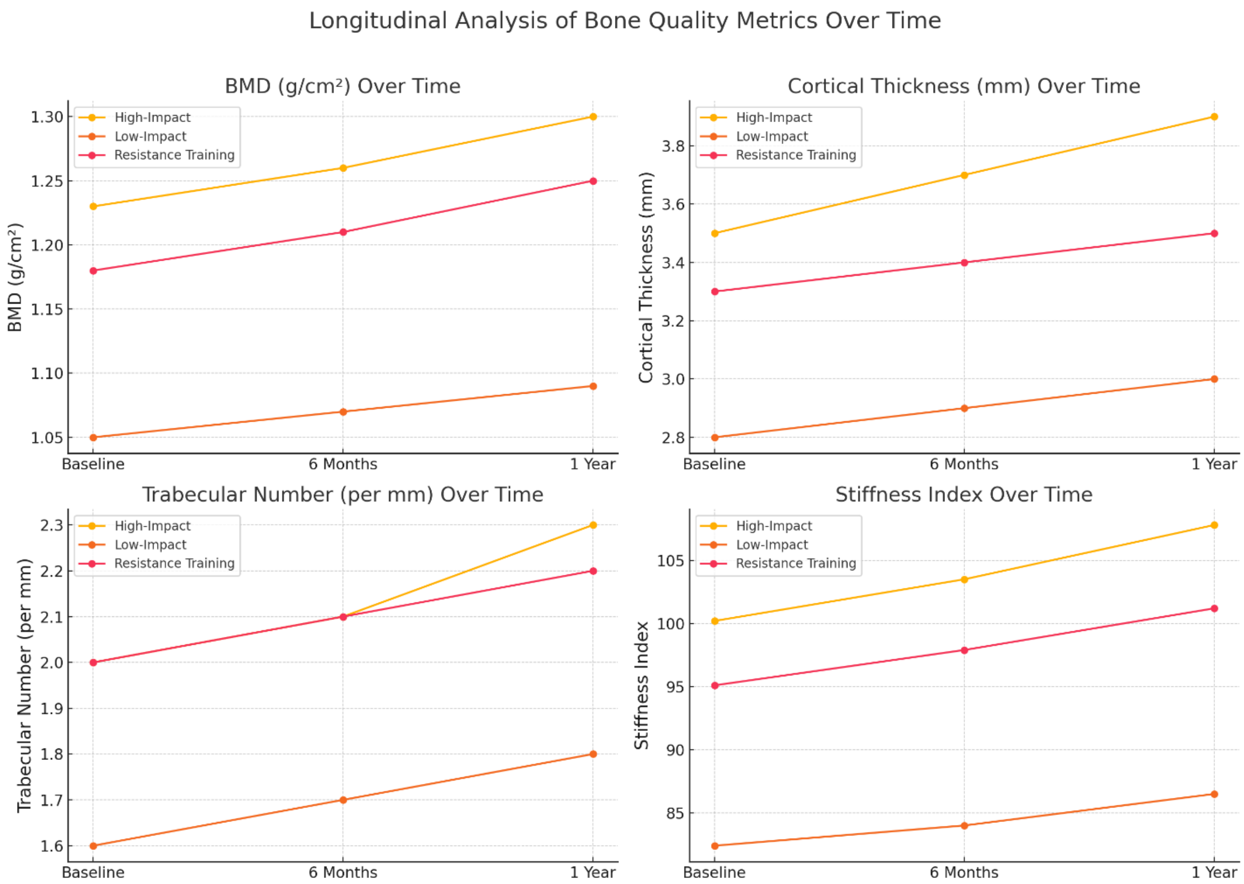

Figure 6. Longitudinal analysis.

The longitudinal analysis in **Table 8** and **Figure 6** illustrates the progression of bone quality metrics over time for different loading modalities: high-impact, low-impact, and resistance training. The findings demonstrate the positive effects of consistent exposure to each type of loading on BMD, cortical thickness, trabecular number, and stiffness index over one year. There is a clear upward trend in BMD for high-impact loading, increasing from 1.23 g/cm² at baseline to 1.30 g/cm² at the one-year mark. Cortical thickness also improves, rising from 3.5 mm to 3.9 mm, while the mean trabecular number increases from 2.0 to 2.3 per mm. The stiffness index shows a substantial improvement, from 100.2 at baseline to 107.8 at the one-year mark. These consistent gains indicate that high-impact activities, characterized by high mechanical load and frequent jumping and landing, significantly enhance bone structure and strength over time.

In contrast, the low-impact loading group exhibits modest improvements across all bone metrics. BMD rises from 1.05 g/cm² at baseline to 1.09 g/cm² after one year. Similarly, cortical thickness slightly increases from 2.8 mm to 3.0 mm, and the trabecular number progresses slightly from 1.6 to 1.8 per mm. The stiffness index also increases from 82.4 to 86.5 over the year. These minor changes suggest that low-impact activities, which involve reduced mechanical stress, provide a limited stimulus for bone adaptation compared to high-impact activities. For the resistance training group, the results reveal moderate but steady improvements in bone quality metrics. BMD improves from 1.18 g/cm² at baseline to 1.25 g/cm² at the one-year mark, while cortical thickness increases from 3.3 mm to 3.5 mm. The mean trabecular number rises from 2.0 to 2.2 per mm, and the stiffness index advances from 95.1 to 101.2. These changes indicate that resistance training, which involves targeted mechanical loading, significantly impacts bone health, though the effects are not as pronounced as those seen in high-impact sports.

Table 9. Pairwise comparisons of bone quality metrics between loading modalities.

Comparison	Metric	Mean Difference	Confidence Interval (95%)	*p*-value
High-Impact vs. Low-Impact	BMD (g/cm²)	0.21	[0.12, 0.30]	0.001
High-Impact vs. Resistance	BMD (g/cm²)	0.07	[0.01, 0.13]	0.042
Low-Impact vs. Resistance	BMD (g/cm²)	−0.14	[−0.22, −0.07]	0.002
High-Impact vs. Low-Impact	Cortical Thickness	0.8 mm	[0.5 mm, 1.1 mm]	<0.001
High-Impact vs. Resistance	Cortical Thickness	0.4 mm	[0.1 mm, 0.7 mm]	0.035
Low-Impact vs. Resistance	Cortical Thickness	−0.4 mm	[−0.6 mm, −0.2 mm]	0.014
High-Impact vs. Low-Impact	Stiffness Index	22.5	[17.8, 27.2]	<0.001
High-Impact vs. Resistance	Stiffness Index	9.1	[4.3, 13.9]	0.003
Low-Impact vs. Resistance	Stiffness Index	−13.4	[−18.0, −8.8]	0.001

The pairwise comparisons detailed in **Table 9** and **Figure 7** provide insight into the significant differences in bone quality metrics between loading modalities, specifically comparing high-impact, low-impact, and resistance training. These comparisons reveal how the intensity and type of loading influence BMD, cortical thickness, and stiffness index among athletes. The analysis shows that high-impact activities lead to the most pronounced differences in BMD compared to low-impact and resistance training modalities. The mean BMD difference between high-impact and low-impact groups is 0.21 g/cm² (95% CI: [0.12, 0.30], p = 0.001), indicating a statistically significant and substantial increase associated with high-impact loading. This is further supported by the difference between high-impact and resistance groups (0.07 g/cm², 95% CI: [0.01, 0.13], p = 0.042), suggesting that while resistance training enhances BMD, high-impact activities have a more substantial effect. Conversely, the negative mean difference between low-impact and resistance training (−0.14 g/cm², 95% CI: [−0.22, −0.07], p = 0.002) highlights that low-impact activities are less effective at improving BMD compared to resistance-based loading.

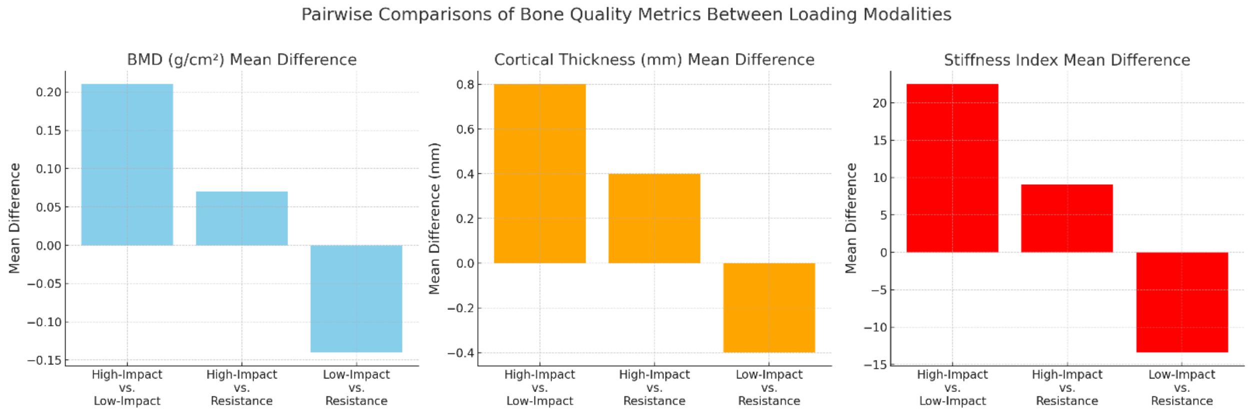

Figure 7. Pairwise comparisons.

When examining cortical thickness, the findings demonstrate significant gains in high-impact sports. The mean difference in cortical thickness between high-impact and low-impact groups is 0.8 mm (95% CI: [0.5 mm, 1.1 mm], p < 0.001), reflecting the substantial structural benefits associated with high-impact loading. The comparison between high-impact and resistance groups shows a more minor but still significant difference of 0.4 mm (95% CI: [0.1 mm, 0.7 mm], p = 0.035), indicating that resistance training contributes to increased cortical thickness but not as effectively as high-impact exercises. The negative difference between low-impact and resistance −0.4 mm, 95% CI: [−0.6 mm, −0.2 mm], p = 0.014) further emphasizes the limited impact of low-intensity activities on bone structure development. The stiffness index comparisons reinforce the significant influence of loading modality on bone health. High-impact activities show the most considerable mean difference in stiffness index compared to low-impact groups, with a value of 22.5 (95% CI: [17.8, 27.2], p < 0.001). This indicates that high-impact exercises significantly enhance bone stiffness, improving overall bone quality. When comparing high-impact to resistance training, the mean difference in stiffness index is 9.1 (95% CI: [4.3, 13.9], p = 0.003), suggesting that while resistance training is beneficial, it is not as effective as high-impact loading in improving stiffness. The comparison between low-impact and resistance modalities (−13.4, 95% CI: [−18.0, −8.8], p = 0.001) illustrates that low-impact activities significantly enhance bone stiffness.

Table 10. Effect size calculations for bone quality metrics across loading modalities.

Metric	Comparison	Effect Size (Cohen's d)	Interpretation	Partial Eta Squared (η^2)	Interpretation
BMD (g/cm²)	High-Impact vs. Low-Impact	0.86	Large Effect	0.29	Moderate Effect
	High-Impact vs. Resistance	0.35	Small to Medium Effect	0.12	Small Effect
	Low-Impact vs. Resistance	0.74	Medium to Large Effect	0.25	Moderate Effect
Cortical Thickness	High-Impact vs. Low-Impact	1.10	Large Effect	0.35	Large Effect
	High-Impact vs. Resistance	0.55	Medium Effect	0.18	Small to Moderate Effect
	Low-Impact vs. Resistance	0.67	Medium Effect	0.21	Moderate Effect
Stiffness Index	High-Impact vs. Low-Impact	1.45	Very Large Effect	0.38	Large Effect
	High-Impact vs. Resistance	0.79	Large Effect	0.28	Moderate Effect
	Low-Impact vs. Resistance	1.10	Large Effect	0.34	Large Effect

The effect size calculations detailed in **Table 10** and **Figure 8** provide a quantitative measure of the magnitude of differences between loading modalities on bone quality metrics, including BMD, cortical thickness, and stiffness index. These effect sizes, expressed using Cohen's d and partial eta squared (η^2), help interpret the practical significance of these differences beyond statistical significance, offering a clearer understanding of the impact of various loading types on bone health.

For BMD, the comparison between high-impact and low-impact groups shows a Cohen's d of 0.86, indicating a significant effect. This substantial effect size suggests that high-impact activities significantly increase BMD compared to low-impact exercises. The corresponding partial eta squared value of 0.29 indicates a moderate effect, reinforcing that high-impact loading effectively improves bone density. The effect size between high-impact and resistance training (Cohen's d = 0.35) shows a small to medium effect, while the η^2 value of 0.12 indicates a small effect, highlighting that while resistance training does contribute positively to BMD, the impact is not as strong as that of high-impact activities. Conversely, the comparison between low-impact and resistance training (Cohen's d = 0.74) reveals a medium to significant effect, with an η^2 value of 0.25, indicating that resistance training is more effective than low-impact activities in enhancing BMD.

When evaluating cortical thickness, the effect size between high-impact and low-impact loading is particularly pronounced, with a Cohen's d of 1.10, signifying a significant effect. This is corroborated by the η^2 value of 0.35, which indicates a significant effect, suggesting that high-impact activities greatly enhance cortical thickness. The comparison between high-impact and resistance training (Cohen's d = 0.55) shows a medium effect, while the η^2 value of 0.18 suggests a small to moderate effect, demonstrating that although resistance exercises improve cortical thickness, they are less effective than high-impact sports. Similarly, the effect size between low-impact and resistance training (Cohen's $d = 0.67$) represents a medium effect, and the η^2 value of 0.21 suggests a moderate effect, confirming that resistance training is more beneficial than low-impact activities for enhancing cortical structure.

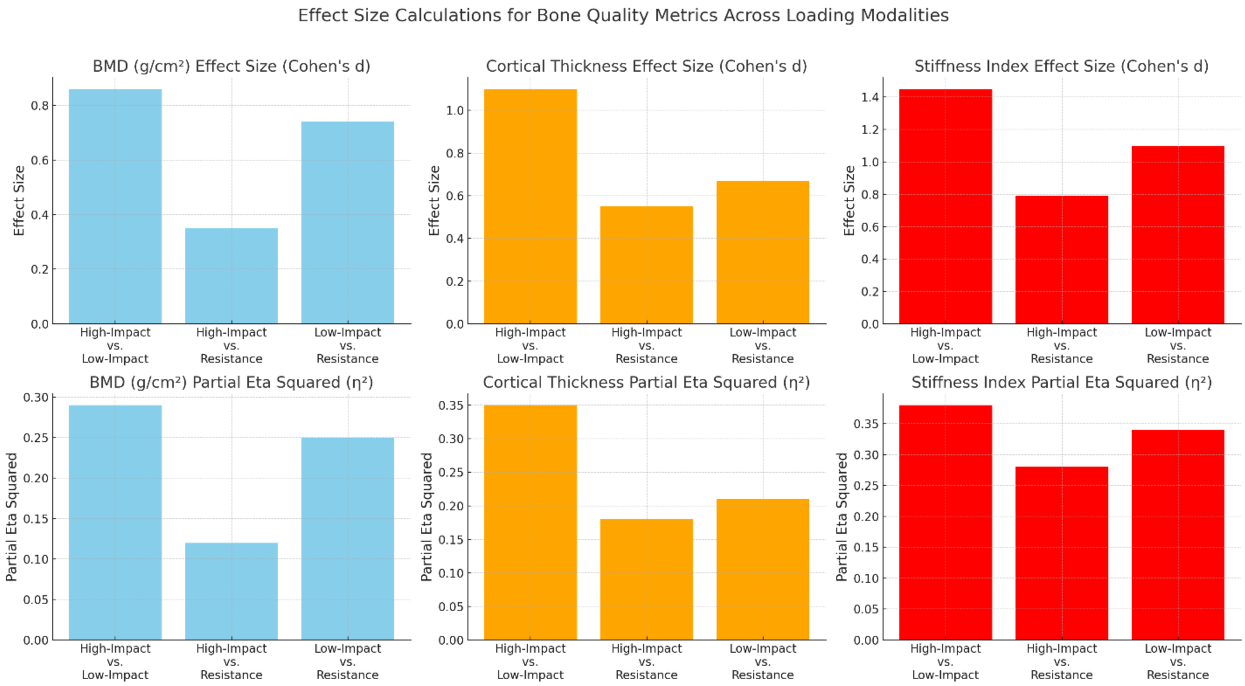

Figure 8. Effect size calculations.

The stiffness index shows the most pronounced differences among the groups. The comparison between high-impact and low-impact loading yields a Cohen's d of 1.45, indicating an enormous effect. The η^2 value of 0.38 further emphasizes a significant effect, highlighting that high-impact activities positively impact bone stiffness significantly. The high-impact versus resistance comparison (Cohen's $d = 0.79$) demonstrates a significant effect, with an η^2 value of 0.28 indicating a moderate effect, confirming that while resistance training positively influences stiffness, the effect is not as strong as high-impact exercises. The comparison between low-impact and resistance (Cohen's $d = 1.10$) shows a significant effect, supported by an η^2 value of 0.34, indicating that resistance training is significantly more effective in enhancing stiffness than low-impact modalities.

5. Conclusion and future work

This study demonstrates the significant impact of different loading modalities on bone quality among athletes, highlighting the superior benefits of high-impact activities in enhancing BMD, cortical thickness, and overall bone structure. Resistance training also shows positive effects, particularly in localized areas directly influenced by targeted loading, while low-impact activities offer limited bone-strengthening benefits. Integrating multiple advanced diagnostic techniques—DXA, QUS, and pQCT—provides a comprehensive and multidimensional assessment of bone quality, offering valuable insights into the structural and mechanical adaptations induced by various sports. Additionally, the analysis of demographic factors reveals that age and gender play crucial roles in bone adaptation, necessitating tailored training programs to optimize bone health for different athlete groups.

The findings underscore the importance of specific and appropriate loading modalities for maximizing bone development and preventing injury. These insights have practical implications for sports professionals, athletes, and healthcare providers aiming to promote skeletal health through informed and scientifically validated training strategies.

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