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Research article

EXERCISE CAPACITY IN YOUTH 3X3 BASKETBALL: A COMPARATIVE ANALYSIS BETWEEN U15 AND U17 CATEGORIES

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Abstract

Analyzing effort parameters in 3x3 basketball is necessary due to game intensity, providing coaches with an accurate perspective on the physical components that require optimization in athlete training. This study compares the heart rate and movement profiles of U17 (n = 10, born 2009) and U15 (n = 10, born 2011) players from the ACS MADMAX Iași club in Romania. The players were monitored with Polar GPS chest straps during two training sessions on October 31, 2025. The analyzed metrics are effort distribution across zones Z1–Z5, individual player variation, and movement efficiency. The U15 group showed higher physical stress during training: an average Cardio Load (CL) of 42.1 vs. 17.2, time in Z4+Z5 of 26.1% vs. 0.5%, and an average heart rate (HR Avg) of 71.9% vs. 59.4% of maximum heart rate (HR max). The distance-to-Cardio Load ratio (km/CL) was higher in the U17 group (0.081 vs. 0.040 km/unit), showing better movement efficiency. Analyzing these two age groups reveals how physical growth changes a player's response to the same training exercises. The data help identify specific individual needs within each category to optimize game-based conditioning.

Keywords*: 3x3 basketball, youth athletes, heart rate monitoring, training intensity zones, athletic periodization.*

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1. Introduction

For athletic structures and youth training frameworks to be considered genuinely sustainable, they must achieve a balanced integration of four fundamental dimensions: social impact, environmental preservation, economic viability, and institutional integrity (Yang et al., 2020). The fast growth of 3x3 basketball worldwide, especially after its Tokyo 2020 Olympic debut, has changed how young players develop and compete. Its specific rules, such as the fast pace, 12-second shot clock, and continuous play (Sansone et al., 2023), create intense physical demands that differ significantly from traditional 5x5 basketball. Elite 3x3 games keep players at near-maximal heart rate (HR) responses and cause neuromuscular fatigue (Sansone et al., 2023).

In modern sports training management, the accurate quantification and monitoring of training load are essential for optimizing athletic performance and reducing health-related risks. This issue is particularly important in youth sports, where inappropriate workloads may impair development and increase the risk of injury and psychological stress (Bergeron et al., 2015). Additionally, the morphofunctional characteristics of young athletes contribute to substantial inter-individual variability in responses to training stimuli (Clemente et al., 2020). More specifically, the transition from the Under-15 (U15) to the Under-17 (U17) category is associated with rapid bone and muscle growth, cardiovascular development, and metabolic adaptations (Montgomery & Maloney, 2018), further emphasizing the need for individualized workload management.

The personal contribution of the author is the direct, synchronized field-monitoring of youth physical output within a real competitive framework. Therefore, the purpose of this study is to compare the physiological and locomotor profiles of U17 and U15 youth 3x3 basketball players. To achieve this, I recorded the players' live cardiac responses across five intensity zones and calculate their distance to load ratios during high-intensity tournament simulations.

2. Material and method

I studied 20 male youth basketball players from the same sports club, ACS MADMAX Iași, Romania. The players were divided into two groups based on their competitive age category: the U17 group (n = 10) and the U15 group (n = 10). This study is limited by its small size involving 20 total subjects (n = 10 per group) and its focus on a single session, applying this monitoring protocol across a full competitive season would provide a more comprehensive dataset and allow for stronger generalizations.

Both teams followed the same training schedule of four sessions per week. We collected all data on October 31, 2025, in the same basketball gymnasium to ensure identical indoor conditions. To avoid the influence of different times of day, the groups played back-to-back: the U17 group started at 11:47 (session duration: 28 min., 10 s.), and the U15 group started at 13:31 (session duration: 31 min., 52 s.). Before playing, all participants completed a regular 15 minute warm-up consisting of running, dynamic stretching, and ball-handling drills.

The integration of GPS-based monitoring systems and physiological parameters, including heart rate (HR), maximum heart rate (HRmax), and Cardio Load, has become essential in modern sports science. These technologies provide accurate, individualized insights into athletes' internal and external training loads, thereby supporting performance optimization, fatigue management, and injury prevention (Impellizzeri et al., 2019; Peake et al., 2018; Martins et al., 2021)

During the games, each player wore a wireless cardio-GPS sensor secured to the chest with an elastic strap (Polar Team Pro). The devices tracked real-time movement and cardiac parameters, transmitting the data to a sports performance analysis platform to generate individual and group reports.

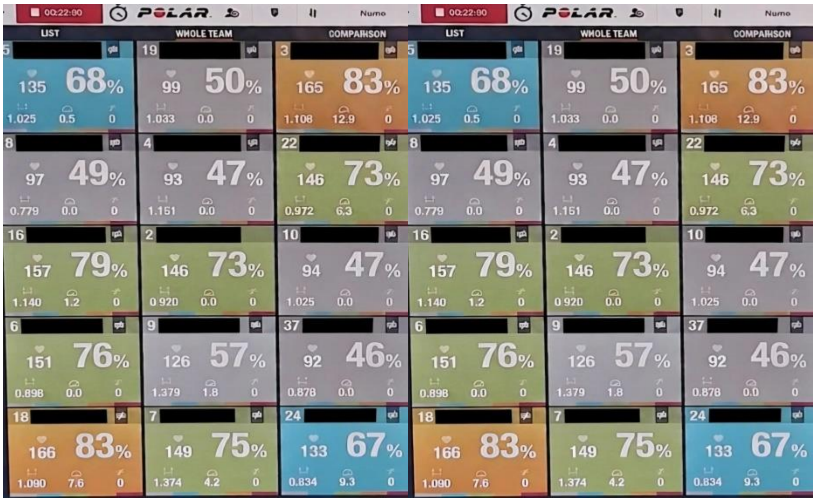
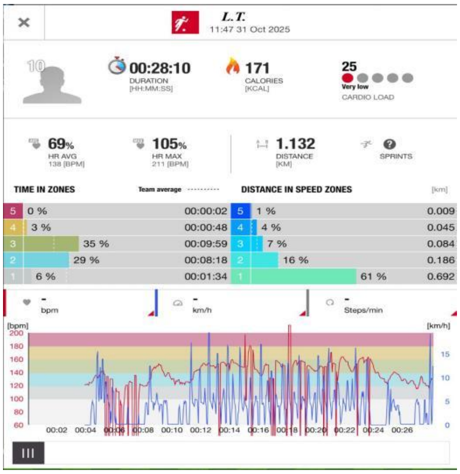


Fig. 1- Real-time physiological monitoring of the U17 team

The monitored parameters included session duration, calories consumed (kcal), Cardio Load (CL), average heart rate (HR Avg), maximum heart rate (HR Max), total distance covered (km), and the percentage distribution of time and distance across five cardiac effort zones (Z1–Z5).



L.T.
11:47 31 Oct 2025

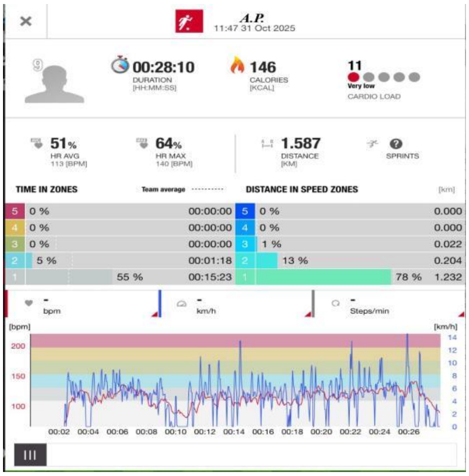
10

00:28:10 DURATION [HH:MM:SS]
171 CALORIES [KCAL]
25 Very low CARDIO LOAD

69% HR AVG 138 [BPM]
105% HR MAX 211 [BPM]
1.132 DISTANCE [KM]
? SPRINTS

TIME IN ZONES			DISTANCE IN SPEED ZONES		[km]
5	0 %	00:00:02	5	1 %	0.009
4	3 %	00:00:48	4	4 %	0.045
3	35 %	00:09:59	3	7 %	0.084
2	29 %	00:08:18	2	16 %	0.186
1	6 %	00:01:34	1	61 %	0.692

Fig. 2- Individual physiological data – L.T.



A.P.
11:47 31 Oct 2025

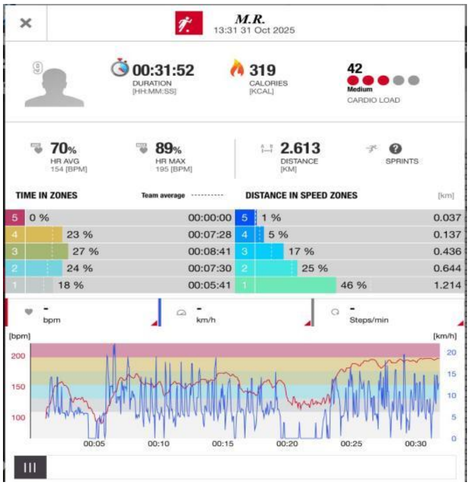
9

00:28:10 DURATION [HH:MM:SS]
146 CALORIES [KCAL]
11 Very low CARDIO LOAD

51% HR AVG 113 [BPM]
64% HR MAX 140 [BPM]
1.587 DISTANCE [KM]
? SPRINTS

TIME IN ZONES			DISTANCE IN SPEED ZONES		[km]
5	0 %	00:00:00	5	0 %	0.000
4	0 %	00:00:00	4	0 %	0.000
3	0 %	00:00:00	3	1 %	0.022
2	5 %	00:01:18	2	13 %	0.204
1	55 %	00:15:23	1	78 %	1.232

Fig. 3- Individual physiological data – A.P



M.R.
13:31 31 Oct 2025

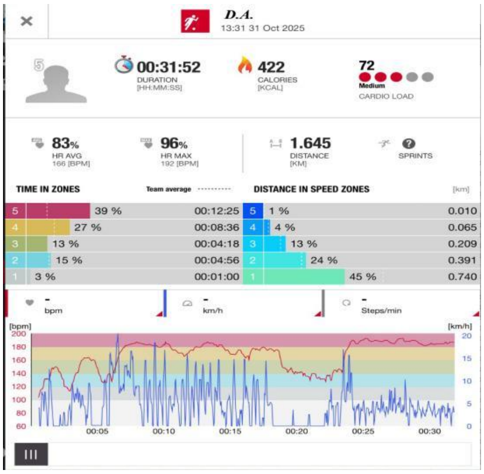
9

00:31:52 DURATION [HH:MM:SS]
319 CALORIES [KCAL]
42 Medium CARDIO LOAD

70% HR AVG 154 [BPM]
89% HR MAX 195 [BPM]
2.613 DISTANCE [KM]
? SPRINTS

TIME IN ZONES			DISTANCE IN SPEED ZONES		[km]
5	0 %	00:00:00	5	1 %	0.037
4	23 %	00:07:28	4	5 %	0.137
3	27 %	00:08:41	3	17 %	0.436
2	24 %	00:07:30	2	25 %	0.644
1	18 %	00:05:41	1	46 %	1.214

Fig.4 Individual physiological data – M.R.



D.A.
13:31 31 Oct 2025

5

00:31:52 DURATION [HH:MM:SS]
422 CALORIES [KCAL]
72 Medium CARDIO LOAD

83% HR AVG 166 [BPM]
96% HR MAX 192 [BPM]
1.645 DISTANCE [KM]
? SPRINTS

TIME IN ZONES			DISTANCE IN SPEED ZONES		[km]
5	39 %	00:12:25	5	1 %	0.010
4	27 %	00:08:36	4	4 %	0.065
3	13 %	00:04:18	3	13 %	0.209
2	15 %	00:04:56	2	24 %	0.391
1	3 %	00:01:00	1	45 %	0.740

Fig. 5 -Individual physiological data – D.A.

Figures 2 and 3 illustrate these individual physiological profiles for the U17 category, while Figures 4 and 5 represent the U15 category, all generated by the Polar Team Pro platform (Polar Electro Kempele, Finland). Each report provides a comprehensive overview of the athlete's workload.

3. Findings

Individual physiological profile – U17/2009 Group

Table 1 presents the individual physiological parameters of players in the U17/2009 Group

Player	**No.**	**Kcal**	**C.Load**	**Level**	**HR Avg%**	**HR Avg BPM**	**HR Max%**	**HR Max BPM**	**Dist (km)**	**Z5t%**	**Z4t%**	**Z3t%**	**Z2t%**	**Z1t%**
S.T.	12	158	20	Low	65	129	78	155	1.093	0	0	19	40	18
V.A.	6	127	9	Very low	50	100	65	129	1.167	0	0	0	2	48

Player	No.	Kcal	C.Load	Level	HR Avg%	HR Avg BPM	HR Max%	HR Max BPM	Dist (km)	Z5t%	Z4t%	Z3t%	Z2t%	Z1t%
R.R.	8	166	20	Low	64	127	74	148	1.022	0	0	11	56	18
C.C.	11	138	12	Medium	55	109	64	127	1.074	0	0	0	8	71
P.M.	17	225	26	Very low	65	130	80	159	1.259	0	0	27	50	23
L.T.	15	171	25	Very low	69	138	105	211	1.132	0	3	35	29	6
B.D.	20	215	28	Very low	68	135	81	161	1.122	0	1	28	59	7
A.P.	14	146	11	Very low	51	113	64	140	1.587	0	0	0	5	55
J.S.	20	137	11	Low	55	110	75	150	0.973	0	0	2	10	58
D.S.	18	115	10	-	52	105	89	177	0.768	0	1	0	7	49
MEAN		**159.80**	**17.20**		**59.40**	**119.60**	**77.50**	**155.70**	**1.12**	**0.00**	**0.50**	**12.20**	**26.60**	**35.30**

Table 1. Individual physiological parameters and effort zone distribution – U17/2009 Group (n=10, duration 28:10 min)

Individual physiological profile – U15/2011 Group

Table 2 presents the individual physiological parameters of players in the U15/2011 Group, using the same indicators as in Table 1.

Table 2. Individual physiological parameters and effort zone distribution – U15/2011 Group

Player	No.	Kcal	C.Load	Level	HR Avg%	HR Avg BPM	HR Max%	HR Max BPM	Dist (km)	Z5t%	Z4t%	Z3t%	Z2t%	Z1t%
D.A.	19	422	72	Medium	83	166	96	192	1.645	39	27	13	15	3
L.D.	2	337	67	Medium	82	164	97	193	1.602	21	43	19	13	1
H.I.	5	339	55	Medium	76	152	97	194	1.307	22	16	24	29	9
T.C.	10	195	31	Medium	63	125	94	188	1.465	9	14	5	10	31
C.R.	6	320	60	Medium	81	161	99	197	2.022	27	15	37	11	2
M.R.	9	319	42	Medium	70	154	89	195	2.613	0	23	27	24	18
M.D.	3	270	31	Medium	69	138	82	164	1.345	0	4	39	50	5
D.T.	19	149	22	Very low	69	137	80	159	1.075	0	0	34	29	8
P.S.	16	125	14	Low	58	117	84	167	0.883	0	0	4	37	20
A.I.	17	224	27	Medium	68	135	81	161	1.502	0	1	36	38	16
MEAN		**270.00**	**42.10**		**71.90**	**144.90**	**89.90**	**181.00**	**1.55**	**11.80**	**14.30**	**23.80**	**25.60**	**11.30**

4. Discussions

A comparative analysis of the mean physiological parameters between the two teams is presented in Table 3, highlighting the distinct cardiovascular and metabolic profiles exhibited by each group during training.

Table 3. Comparison of mean physiological parameters – U17/2009 Group vs. U15/2011 Group

Parameter	G2009/U17 (n=10)	G2011/U15 (n=10)	Difference (G2−G1)
Session duration	28:10 min	31:52 min	**+3:42**
Mean calories (kcal)	159.80	270.00	**110.2**
Mean Cardio Load	17.20	42.10	**24.9**

Parameter	**G2009/U17 (n=10)**	**G2011/U15 (n=10)**	**Difference (G2−G1)**
Mean HR Avg %	59.40	71.90	**12.5**
Mean HR Avg BPM	119.60	144.90	**25.3**
Mean HR Max %	77.50	89.90	**12.4**
Mean HR Max BPM	155.70	181.00	**25.3**
Mean distance (km)	1.12	1.55	**0.430**
% time Z5 (maximal)	0.00	11.80	**11.8**
% time Z4 (high)	0.50	14.30	**13.8**
% time Z3 (medium)	12.20	23.80	**11.6**
% time Z2 (moderate)	26.60	25.60	**-1.0**
% time Z1 (light)	35.30	11.30	**-24.0**

Data from the training session reveals a clear age-based disparity: the younger group (G2011/U15) sustained a much higher physical and cardiovascular load compared to the older G2009/U17 athletes. Although the difference in session duration was minor (+3:42 min for U15), the U15 players registered a 69% higher energy expenditure (270.00 vs. 159.80 kcal) and a mean Cardio Load nearly 2.5 times greater than the U17 group (42.10 vs. 17.20). This massive discrepancy is directly supported by the heart rate metrics, where the U15 group operated at a mean of 71.90% HRmax and reached a peak of 89.90% HRmax, while the U17 group remained in a predominantly submaximal zone (59.40% HRmax mean). The distribution of time across intensity zones clearly explains this polarization: while the U17 athletes completely avoided the maximal zone (Z5) and spent a combined 61.9% of the session in light and moderate brackets (Z1-Z2), the U15 players spent over a quarter of the training volume under high-intensity and maximal thresholds (Z4-Z5), while also covering a greater absolute distance (1.55 km vs. 1.12 km).

From a physiological standpoint, the variations between the U17 and U15 teams are related to biological developmental stages. While the older players showed stable cardiac responses to submaximal workloads due to an age-related improvement in managing their own pacing, the U15 team operated under intense cardiovascular strain. Younger, less mature athletes frequently sustain efforts within peak cardiovascular thresholds (Z5 > 90% HR max) often lacking the pacing efficiency required to regulate internal load during uniform team constraints.

Table 4. Inter-individual variability indicators – U15/2011 Group

Parameter	**Mean**	**Min**	**Max**	**Range (Max−Min)**	**CV% (est.)**
Calories (kcal)	270.00	125.00	422.00	297.00	55.0%
Cardio Load	42.10	14.00	72.00	58.00	68.9%
HR Avg %	71.90	58.00	83.00	25.00	17.4%
HR Avg BPM	144.90	117.00	166.00	49.00	16.9%
HR Max %	89.90	80.00	99.00	19.00	10.6%
HR Max BPM	181.00	159.00	197.00	38.00	10.5%
Distance (km)	1.55	0.90	2.60	1.70	54.8%

Table 4 highlights the large individual variations within the U15 team, demonstrating that identical training constraints generated highly unequal physical and metabolic responses. This dispersion is most prominent in the internal workload metrics. Cardio Load varied by 58.00 (CV = 68.9%), separating the least taxed player (14.00 units) from the most physically challenged one (72.00 units), with a parallel 297.00 kcal gap in energy expenditure (CV=55.0%). Mechanical volume also differed significantly (CV= 54.8%), as total distance more than doubled from a minimum of 0.883 km to a maximum of 2.613 km. Meanwhile, relative heart rate parameters remained highly uniform, showing lower variability in both mean (CV = 17.4% HRavg) and peak cardiovascular values (CV= 10.6%

HRmax). These indicators demonstrate that while the entire group consistently achieved near-maximal cardiac recruitment, the mechanical work performed and the resulting total internal costs were highly asymmetric.

Categorizing this intensity into distinct heart rate zones provides a precise method for monitoring internal load, revealing substantial inter-individual variability across both teams. This wide dispersion reflects the marked individual variations in biological maturation typical around 14 years of age. Within the U15 group alone, individual CL ranged from 14 (P.S.) to 72 (D.A.), while total distance ranged from 0.883 km to 2.613 km. This demonstrates the critical importance of individualized internal load monitoring.

This approach is heavily supported by recent acute profiling which indicates that recreational 3×3 basketball structures can elicit similar or even superior physiological stimuli and enjoyment levels compared to traditional high-intensity interval training (HIIT) protocols (Buchheit, M., & Laursen, P.B. 2013). However, while such indicators have been predominantly validated in active young adults with established tactical experience, their direct translation to younger subjects remains a critical area of investigation. The pronounced physiological stress observed in the U15 team is indicated by a substantially higher Cardio Load and an average heart rate of 71.9% of their maximum. This reflects the inherent, high-density nature of half-court play. Official medical tracking and performance tests confirm that the work-to-rest density in 3x3 basketball is twice as high as in traditional 5v5 basketball (Montgomery et al., 2018). Adolescent athletes within early developmental stages, such as the U15 group, do not possess a fully developed aerobic capacity required to rapidly clear the metabolic by products and lactic acid accumulated during these phases of continuous, explosive effort. This physiological limitation explains why their heart rates remain effectively "locked" in the upper intensity zones (Z4–Z5) throughout the short training sessions.

Therefore, training strategies must be individualized. The U17 team requires targeted intensity progression, shifting more volume into the Z3–Z4 through fast-paced bilateral play (Sansone et al., 2023). Meanwhile, outlier profiles like V.A. and D.S. suggest a need for targeted aerobic conditioning; integrating high-intensity interval training (HIIT) or specific small-sided games can enhance their maximal oxygen uptake (VO2max) and cardiovascular efficiency, allowing them to effectively tolerate higher competitive demands (Buchheit & Laursen, 2013).

5. Conclusions

This study highlights differences in how U17 and U15 players respond to 3x3 basketball, showing that integrated cardio-GPS monitoring provides a reliable, objective method for tracking training loads. The U15 group experienced higher cardiovascular stress, spending more time in high-intensity zones (Z3–Z5). The distance to cardio-load ratio indicates that U17 players possess better locomotor efficiency and a more developed movement economy. As a result, youth 3x3 basketball coaching requires continuous, standardized workload tracking rather than a uniform approach. Training plans must be adapted to match each athlete's biological maturity and individual internal effort profile.

Furthermore, this investigation underscores that looking only at team averages can be misleading. Coaches must account for the high intra-group dispersion in mechanical volume and metabolic costs, particularly within younger teams where biological maturation rates vary. Practically, field practitioners should implement targeted interventions, such as high-intensity interval training (HIIT) or rule conditioned small-sided games to accelerate aerobic conditioning in outlier profiles. At the same time, training for older athletes should be structured to intentionally push them into higher intensity zones (Z3–Z4) through fast-paced bilateral structures.

In conclusion, this study highlights the importance of individualized workload monitoring during short 3x3 basketball sessions and provides a clearer understanding of the physical demands experienced by young athletes. Longitudinal monitoring across an entire competitive season could offer deeper insight into how players gradually adapt their pacing strategies, heart rate responses, and movement patterns to the sustained demands of competitive basketball (Stojanović et al., 2018).

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Review article

OSTEOPENIA AND VIBRATION THERAPY: A BRIEF NARRATIVE REVIEW

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Abstract

The skeleton is a tissue that undergoes constant remodelling throughout one’s life. This is necessary to allow the skeleton develop during growth, respond to the stresses placed on it, and repair structural damage caused by structural fatigue or fracture.

There are three major phases throughout which bone mass changes during one’s life: growth, consolidation, and involution. Involutional bone loss starts between the ages of 35 and 40 in both sexes, but in women it is accelerated after the menopause begins.

Osteopenia refers to the reduced bone mineral density below normal values without passing the diagnostic limit for osteoporosis.

Vibration therapy uses mechanical vibrations to contract and relax the muscles. Vibrations pass through the body while the patient stands, sits or lies on a machine. Generally, it can take two forms: Whole-Body Vibration (WBV) or Focal Vibration (FV). During vibration, skeletal muscles rapidly contract and relax at a certain chosen frequency, which promotes muscle anabolism and improved stretch reflex through the activation of one’s muscle spindles.

While some studies show that it promotes increases in the bone density, alongside stimulating bone remodelling and generally being an innovative exercise alternative that has a potential use in metabolic disease and in situations in which patients are unable to perform traditional exercises, the evidence is still mixed or contradictory.

The purpose of this article is to review the recent literature regarding the use of vibration therapy in treating bone metabolic disorders and outline potential avenues for future investigation and clinical implementation.

***Keywords**:* Osteopenia, Vibration therapy, Whole-Body Vibration

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1. Introduction

Bone is a living, dynamic tissue that undergoes constant remodelling throughout life. This is necessary to allow the skeleton to increase in size during growth, respond to the physical stresses placed on it, and repair structural damage caused by structural fatigue or fracture. The processes of bone resorption and bone formation are usually closely coupled, but bone formation exceeds resorption during skeletal growth, allowing the skeleton to increase in size and density. Later in life resorption outstrips bone formation, leading to involutional bone loss.

Bone mass changes throughout life in three major phases: growth, consolidation, and involution. Up to 90% of the ultimate bone mass is deposited during skeletal growth, which lasts until the closure of the epiphyses. There is then a phase of skeletal consolidation lasting for up to 15 years, when bone mass increases further until the peak mass is achieved in the mid-30s. Involutional bone loss then starts between the ages of 35 and 40 in both sexes, but in women there is an acceleration of bone loss in the decade after the menopause (Fillit et al., 2016, p. 565).

Osteopenia, or low bone mass, refers to reduced bone mineral density below normal values without fulfilling the diagnostic threshold for osteoporosis. Bone mineral density is determined by dual-energy x-ray absorptiometry (DXA). According to the World Health Organization, osteopenia corresponds to a T-score between -1.0 and -2.5, while a T-score less than -2.5 indicates osteoporosis. Osteopenia arises from an imbalance between bone resorption and formation, influenced by aging, estrogen deficiency, inadequate calcium and vitamin D intake, cigarette smoking, a sedentary lifestyle, and certain medications such as glucocorticoids (Varacallo et al., 2026).

The human skeleton is not a static structure; it a metabolically active tissue in a state of continuous remodelling. This ongoing remodeling serves several essential functions: ensuring skeletal growth, adapting to different types of mechanical load, and repairing microdamage before it progresses to an actual fracture.

Under normal circumstances, bone resorption and bone formation are 2 complementary processes. During growth, however, the formation is the main process, allowing the skeleton to expand in both size and mineral density. With advancing age, this balance scales in the opposite direction, and resorption begins to outpace formation which in time leads to bone loss.

Skeletal mass evolves across three broad phases. The first, the growth phase, accounts for roughly 90% of the eventual bone mass formation, ending with the epiphyseal closure. A consolidation phase follows, extending up to 15 years after this point, during which bone mass continues to rise toward its peak, which is typically reached in the mid-30s for both males and females. After that, involutional loss sets in gradually in both men and women from around the age of 35–40. Women, however, face an additional challenge: the years immediately following menopause are associated with an accelerated phase of bone loss that substantially compounds this age-related decline (Fillit et al., 2016, p. 565).

Vibration therapy uses mechanical vibrations to contract and relax the muscle fibers. Vibrations pass through the body while the patient stands, sits or lies on a specific machine. Usually, it can be used in two ways: Whole-Body Vibration (WBV) or Focal Vibration (FV) (Physiopedia, n.d.; Royal Osteoporosis Society, n.d.).

During vibration, muscles oscillate rapidly between contraction and relaxation at a certain calculated frequency, which in turn promotes muscle anabolism and eventual improved stretch reflex through the activation of the targeted muscle spindles.

While some studies show that it promotes increases in the bone density, alongside stimulating bone remodeling and generally being an innovative exercise alternative that has a potential use in metabolic disease and in situations in which patients are unable to perform traditional exercises (National Library of Medicine, n.d), the evidence is still mixed or contradictory (Harvard Health Publishing, 2011).

This narrative review synthesizes findings from 40 different sources containing randomized controlled trials, systematic reviews, meta-analyses, animal/ in vitro studies, and one book chapter examining the effects of vibration therapy on bone health. It must be noted that the literature on axial vibration therapy for osteopenia specifically is still limited, thus, this review extrapolates from the pre-existing adjacent studies: studies on osteoporosis and on WBV more broadly (axial vibration is a mechanistically equivalent delivered through the lower limbs). These extrapolations are mentioned in their given chapters.

We address six main questions: (1) What are the general trends and findings across the present literature and the given sources? (2) What can we extrapolate to osteopenia and axial vibration from the literature? (3) What are the main characteristics of the study populations and which are the most vulnerable groups? (4) What mechanisms does vibration therapy act with on the bone? (5) What are the main limitations and scientific gaps in knowledge at this point? (6) What are the clinical implications of these findings for practice and future research?

2. Main text

1. General trends and findings

Across the sources reviewed, the general image is mixed. Vibration therapy appears capable of slowing or even vaguely reversing bone density decline specifically at the proximal femur and lumbar spine, but the actual effect varies considerably depending on the chosen vibration protocol, population characteristics, intervention duration, and the measurement tools used.

1.1 BMD outcomes: stabilization more reliable than reversal

The most consistent finding across the given studies, including the meta-analyses and the systematic reviews is that vibration therapy is more effective at maintaining the bone mass density compared to actually increasing it in a notable way.

For example, Yin et al. (2024), in a comprehensive overview of 15 systematic reviews involving thousands of participants, explicitly conclude that WBV should be recommended for maintaining bone mass density (BMD) in postmenopausal women rather than improving it. This is a conclusion with direct clinical relevance for the management of osteopenia, where preventing progression to osteoporosis is the primary goal.

That said, several sources show notable positive BMD changes under specific conditions. Regina Dantas Jales de Oliveira et al. (2022), in the largest meta-analysis in the reviewed corpus (23 RCTs, n=2,089), found significant improvements in lumbar spine and trochanter BMD specifically for the protocol combining low frequency (~30 Hz) and low magnitude (~0.3 g) over a high cumulative dose (>7,000 minutes, equivalent to daily 20-minute sessions for approximately one year). Li et al. (2024), in a meta-analysis of 13 RCTs, found significant improvements in both lumbar spine and femoral neck BMD at 6 months, though these effects were not sustained at 12-month follow-up, suggesting either a physiological adaptation plateau or insufficient protocol duration.

Importantly, Sen et al. (2020), one of the few direct RCTs in the osteopenic range (T-score −2.0 to −3.0), found significant BMD gains at the femoral neck (+5.0%, p=0.003) and L2–L4 (+1.3%, p=0.005) after 6 months, alongside functional and quality-of-life improvements, providing evidence that positive BMD effects are achievable in this population.

1.2 Site-specificity: the axial transmission pattern

A mechanical pattern of site-specificity emerges consistently across the literature. Chen et al. (2026), confirmed that the most responsive skeletal sites are those closest to the vibration source: Ward's triangle, the greater trochanter, femoral neck, and L2–L4; all located in the lower axial chain. Effects diminish when it comes to distal sites and are inconsistent at the lumbar spine in aggregate analyses, though subgroup analyses under optimal conditions show some effects.

This pattern is mechanically predictable: vibration enters the body through the feet and is progressively attenuated as it travels up the skeleton. Chen et al. (2026) quantify this precisely, noting that vibration transmissibility peaks at the ankle (10–40 Hz), knee (10–25 Hz), and hip/spine (10–20 Hz), with transmitted power dropping to as little as 1/1000th of platform output at higher frequencies or distal sites. Qin et al. (2019), studying axial vibration through the foot in a bed-rest disuse model, demonstrated significant protective effects specifically at the calcaneus but not at the femoral neck, further confirming the mentioned pattern.

This site-specificity has direct implications for axial vibration therapy design: targeting the calcaneus, tibia, and proximal femur is mechanically sound, while expecting significant lumbar spine effects from standing-platform protocols requires high cumulative doses and optimal transmission conditions (e.g., semi-flexed knees, which Oliveira et al. (2016) and de Oliveira et al. (2022) identify as superior to extended-knee postures for maintaining transmissibility to the spine).

1.3 Protocol heterogeneity: A field-wide challenge

The biggest challenge across the given literature is the high heterogeneity of vibration protocols used across studies. Frequencies range from 8 to 90 Hz, magnitudes from 0.15 g to 12 g, session durations from 1 minute to 1 hour, session frequencies from twice weekly to daily, and intervention durations from 4 weeks to 22 months. This variability means that aggregating results across studies often produces null or highly uncertain pooled effects that hide the real effects found within specific protocol subgroups.

Fratini et al. (2016) demonstrate this exact problem: when all WBV studies are pooled indiscriminately, the weighted mean difference is near zero. But when studies are grouped by a specific parameter, clear significant effects emerge (e.g side-alternating platforms (Bemben, 2020) or magnitudes above 3 g). DadeMatthews et al. (2022), in a meta-analysis of 40 RCTs, found that frequency across the 6–90 Hz range was not a significant moderator of BMD outcomes, suggesting that within the clinically used range, frequency alone is insufficient to predict efficacy, and protocol combinations (e.g. platform type x magnitude x frequency x total cumulative dose) determine outcomes.

1.4 Measurement tool sensitivity

A reccuring theme is the insensitivity of dual-energy X-ray absorptiometry (DXA), which is the most commonly used measurement tool, to the microstructural bone improvements that vibration therapy intends to produce. Rajapakse et al. (2021), in a double-blind RCT, found significant improvements in tibial stiffness (+1.31% vs −2.55% in placebo, $p=0.01$), trabecular bone volume fraction, and vertebral marrow fat fraction by MRI, yet no significant DXA-measured BMD differences between the groups. Bilek et al. (2024) similarly found significant per-protocol benefits using CT-based biomechanical computed tomography (BCT) that were absent on the DXA evaluations. Both studies explicitly attribute this to DXA's inability to detect microstructural changes that are clinically significant for bone strength.

This measurement issue has important implications for the interpretation of the literature: The many studies reporting null DXA results for vibration therapy may be underestimating the effects of vibration therapy rather than accurately characterising the biological effects of the intervention. More sensitive imaging modalities (pQCT, HR-pQCT, BCT, MRI-based stiffness) and biochemical markers are needed for a detailed picture.

1.5 Secondary benefits: consistent and clinically meaningful

Even in studies where BMD effects are equivocal or absent, improvements in musculoskeletal function, balance, and fall-related outcomes are reported with notable consistency. This is clinically significant because, for osteopenic patients, fall prevention is at least as important as BMD improvement. Falls are the proximate cause of over 90% of hip fractures (Beck et al., 2022, Ma et. al., 2016).

Dutra et al. (2016), in 122 osteopenic postmenopausal women over 12 months, found significant improvements in hip flexor strength (+36.7%), back extensor strength (+36.5%), grip strength, arm curl test, flexibility, and Timed Up and Go (TUG) mobility while using low-intensity vibration (<1 g) alone. Guedes De Aguiar et al. (2023), reviewing 8 RCTs with 1,095 participants, found consistent improvements in muscle strength, jump performance, balance, and chair rise performance. Luo et al. (2017), despite finding null BMD results, reported significant improvement in maximal isometric knee extensor strength. Sen et al. (2020) found significant TUG improvements, quality-of-life gains, and a significant reduction in depressive symptoms.

Another element characteristic for vibration therapy would be the pain-reduction potential; Li et al. (2024) found a significant reduction in pain scores in osteoporotic patients. This may be particularly relevant for osteopenic patients with early vertebral loading pain.

2. Extrapolation from adjacent literature

2.1 From osteoporosis to osteopenia

The majority of the clinical literature addresses osteoporosis (T-score ≤ −2.5) rather than osteopenia (T-score −1.0 to −2.5). Direct osteopenia-specific evidence comes from a subset of sources: Kienberger et al. (2022), Dutra et al. (2016), He et al. (2022), Bilek et al. (2024), Rajapakse et al. (2021), parts of Myint Swe et al. (2016) (specifically the Slatkovska and Stolzenberg sub-studies), parts of Oliveira et al. (2016), Tan et al. (2016) (which included 92 participants with osteopenia), and Sen et al. (2020), (with T-scores spanning the osteopenic-osteoporotic boundary).

Extrapolation from osteoporosis to osteopenia can be made given several clinical reasons. First, osteopenia and osteoporosis represent points on a continuum of the same pathological process which is accelerated net bone resorption over bone formation, thus interventions that modify this balance are applicable across the full spectrum. Second, the underlying mechanisms (osteoblast-osteoclast coupling, OPG/RANKL signaling, mechanotransduction) are the same, regardless of disease severity. Third, evidence suggest that the response to vibration therapy may actually be greater in osteopenic than in healthy bone: Fratini et al. (2016) find that the skeleton's sensitivity to WBV is inversely related to baseline BMD, and Steppe et al. (2020) show that in the animal models, the OVX-induced osteoporotic bone shows greater responsiveness to LMHFV than healthy bone.

Marini et al. (2021), in a systematic review focused on combined physical and pharmacological treatment in osteopenia and osteoporosis, found that only one eligible RCT existed in the literature whis is an illustration of how understudied the osteopenia-specific combination therapy space is, and of why extrapolation from the broader osteoporosis literature is currently necessary.

2.2 From Whole-Body Vibration to Axial Vibration

All WBV platform studies reviewed are functionally axial vibration studies in terms of the primary transmission pathway: oscillations enter through the feet and travel upward through the lower limbs to the pelvis and spine. Fratini et al. (2016) specifically notes that vibration delivered through the lower limbs cannot reach the upper body with sufficient intensity to produce meaningful effects there, confirming that WBV is a lower-limb and axial-skeleton therapy.

The most directly analogous studies for axial vibration therapy are those using low-magnitude, low-frequency (≤40 Hz) standing-platform protocols with foot contact as the entry point (Rajapakse et al., 2021; de Oliveira et al.(2022); Qin et al., (2019); Tan et al., (2016), and the Bilek et al. (2024) study of the OsteoBoost wearable belt; the latter being the only study in the current set to apply targeted vibration directly to the lumbar spine and hips rather than through the feet.

The OsteoBoost findings are important for bridging WBV platform evidence to direct axial vibration. In a 12-month RCT of 126 osteopenic postmenopausal women, Bilek et al. (2024) found that adherent users (≥3 sessions/week) experienced 83% less vertebral strength decline and significant preservation of vertebral volumetric BMD compared to sham controls with compliance being the dominant variable. Akbar et al. (2025) confirm that OsteoBoost is now FDA-cleared specifically for osteopenia (T-score −1.0 to −2.49) of the lumbar vertebrae or total hip, delivered at 20–40 Hz with low amplitude. Bilek et al. (2025) additionally report 82% adherence in a real-world home-use context with high usability scores, addressing the practical feasibility concern that has historically limited WBV adoption.

3. Demographics, vulnerable populations, and incidence

3.1 Overview of study populations

Table 1. The demographic characteristics in the key studies reviewed

Study (Year)	n	Age range	% Female	Primary condition
Singh & Varma (2023)	9 trials reviewed	55–84 yrs	~100%	Postmenopausal osteoporosis + geriatric age
Kienberger et al. (2022)	65	56–63 yrs	100%	Osteopenia (T-score −1.0 to −2.5)
Rajapakse et al. (2021)	80	45–65 yrs	100%	Osteopenia / low bone mass
Dutra et al. (2016)	122	≥55 yrs (~63 mean)	100%	Osteopenia (specifically recruited)
He et al. (2022)	67	55–90 yrs (~72–73 mean)	85%	Osteopenia post-TKA
Bilek et al. (2024)	126	~61 yrs mean	100%	Osteopenia (T-score −1.0 to −2.5)
de Oliveira et al. (2022)	2,089 (23 RCTs)	53–82 yrs	100%	Postmenopausal (mixed T-scores)

Study (Year)	n	Age range	% Female	Primary condition
Massini et al. (2025)	202 (7 RCTs)	55–93 yrs	94%	Older adults at fracture risk
DadeMatthews et al. (2022)	~2,000+ (40 RCTs)	7–82 yrs	Predominantly female	Mixed: healthy, postmenopausal, chronic conditions
Zhang et al. (2022)	8,502 (97 RCTs)	Middle-aged to elderly	86%	Osteoporosis / osteopenia (mixed)
Sen et al. (2020)	49 completers	40–65 yrs (~54 mean)	100%	Osteopenia to mild osteoporosis (T-score −2.0 to −3.0)
Ebid et al. (2021)	95	~51 yrs mean	0%	Osteopenia / osteoporosis (male cohort)
Qin et al. (2019)	29	25–48 yrs	41%	Disuse/bed-rest osteopenia (healthy baseline)
Tan et al. (2016)	114	45–≥65 yrs	56%	Osteopenia (n=92) + osteoporosis (n=22)

3.2 Most vulnerable population: postmenopausal women

Across all the sources reviewed, postmenopausal women consistently emerge as both the most studied and most clinically vulnerable population. The biological basis is clear: estrogen withdrawal at menopause accelerates bone resorption by disinhibiting osteoclast activity, leading to bone loss rates of 3–5% per year in the initial postmenopausal years (Singh & Varma, 2023). Tomašević-Todorović et al. (2024) note that osteoporotic vertebral fractures affect approximately 1 in 3 women over 50, compared to 1 in 5 men, establishing the gender disparity in fracture risk.

Within the postmenopausal population, a critical age threshold is identified at 65 years. Marín-Cascales et al. (2018) find that significant femoral neck BMD improvements from WBV are specific to women under 65, with no significant effect in the older subgroup. Tan et al. (2016)similarly find that osteogenic responses to WBV diminish in the ≥65 age group. This suggests that the optimal intervention window for vibration therapy in postmenopausal women is the 50–65 year range coinciding with the highest bone loss rate and greatest potential for intervention to change the trajectory.

3.3 Men: underrepresented but responsive

Men are generally underrepresented in the literature. Zhang et al. (2022), in a network meta-analysis of 97 RCTs with 8,502 participants, counted only 1,174 men versus 7,328 women. Myint Swe et al. (2016) explicitly state that evidence for WBV benefits in elderly men remains insufficient. Chen et al. (2026) note that only 4% of participants across their 14 included RCTs were male.

The notable exception is Ebid et al. (2021), which studied an all-male cohort of 95 men (mean age ~51 years) with osteopenia or osteoporosis. Combined PEMF and exercise (including WBV at 30–40 Hz) produced significant increases in lumbar spine and total hip BMD at 12 weeks, with effects sustained at 6-month follow-up, demonstrating that the pathophysiology and therapeutic response in men are comparable, even if the epidemiological burden is lower. Men with secondary osteoporosis risk factors like hypogonadism, prolonged corticosteroid use or low activity levels) represent a rarely researched group.

3.4 Younger and mixed-sex populations

Qin et al. (2019), studying disuse-induced osteopenia in a bed-rest model with 29 volunteers aged 25–48 (41% female), demonstrate that axial vibration through the foot significantly halves the rate of calcaneus BMD loss compared to controls in a population without age-related osteopenia. This is relevant because it isolates the mechanical effect of vibration from the hormonal side present in postmenopause, suggesting that the osteogenic mechanism is broadly applicable across age and sex. Flores (2018), studying 51 premenopausal women aged 18–26, found significant trochanter BMD increases after just 4 weeks of WBV, establishing that vibration can modulate bone even before peak bone mass is reached with implications for primary prevention guidelines.

3.5 Risk factors and incidence

Tomašević-Todorović et al. (2024) provide a detailed enumeration of osteopenia and osteoporosis risk factors relevant to understanding the target population for vibration therapy:

- Non-modifiable: age ≥50, female sex, Caucasian or Asian ethnicity, genetic predisposition, and slender physique
- Hormonal: estrogen deficiency (menopause, surgical oophorectomy), early menopause (<45 years), androgen deficiency in men
- Lifestyle: sedentary lifestyle, smoking, excess alcohol consumption, low calcium and vitamin D intake
- Medical: prolonged corticosteroid use, rheumatoid arthritis, hyperthyroidism, malabsorption syndromes, and chronic immobilization

Chłystek et al. (2018) note that physical inactivity is among the most modifiable and prevalent risk factors, which is why vibration therapy (which mimics the skeletal loading effects of weight exercise without requiring high amounts of physical effort) is attractive for elderly or mobility-limited patients who cannot engage in conventional exercise programs.

4. Mechanisms of action

Understanding how vibration therapy affects bone at the cellular and molecular level is essential for interpreting clinical findings and creating detailed guidelines. The literature reviewed provides converging evidence for several interacting mechanisms.

4.1 Mechanotransduction and osteocyte signaling

Bone is a mechanosensitive tissue that adapts its mass and architecture in response to mechanical loading. Osteocytes the main and the most abundant cells are the primary mechanosensors. They detect shear stress and transduce mechanical signals into biochemical responses that coordinate osteoblast and osteoclast activity (Olçum et al., 2016, Steppe et al., 2020).

Steppe et al. (2020) review 51 studies of LMHFV(Low-Magnitude High-Frequency Vibration) effects on bone cells and confirm that vibration at low magnitudes (<1 g) and frequencies of 20–90 Hz consistently promotes osteogenesis and suppresses bone resorption at the cellular level. Key osteocyte responses include: downregulation of sclerostin (SOST), a potent inhibitor of the Wnt/β-catenin bone formation pathway, increased gap junctional communication between osteocytes and altered secretory profiles that influence neighbouring osteoblasts and osteoclasts.

4.2 Osteoblast activation and bone formation

Vibration at 30–60 Hz and 0.25–0.5 g increases osteoblast proliferation, matrix mineralization, and upregulates bone-formation markers including alkaline phosphatase (ALP), osteocalcin (OCN), Runx2, bone morphogenetic protein (BMP), Osterix, collagen type I, and OPG (Steppe et al., 2020). He et al. (2022) confirm this in a clinical context, finding significant increases in the bone formation markers P1NP and osteocalcin in osteopenic patients receiving WBV following knee arthroplasty.

Runge et al. (2018), in a rat model, identified prostaglandin E2 (PGE2) elevation at a +74% in the highest vibration group as a key biochemical mediator of vibration-induced bone anabolism, implicating the COX-2 pathway. This provides a distinct mechanistic route from the usual osteocyte-sclerostin pathway and suggests that vibration instead engages in multiple parallel anabolic mechanisms.

4.3 Osteoclast suppression and bone resorption reduction

Aside from the anabolic effects, vibration at 45 Hz and 0.3 g also inhibits osteoclast differentiation, reduces actin ring formation, and suppresses several main resorption genes including cathepsin K, MMP-9, and TRAP (Steppe et al., 2020). Kostyshyn et al. (2023) demonstrate in an obese/immobile rat model that WBV at 50 Hz significantly reduces RANKL expression while increasing OPG expression, shifting the OPG/RANKL ratio toward bone formation and away from resorption.

4.4 Mesenchymal stem cell lineage switching

Rajapakse et al. (2021) identify an additional mechanism with particular relevance to ageing bone: LIV significantly decreased vertebral marrow fat fraction in their RCT, suggesting a shift from adipogenic to osteoblastic differentiation of bone marrow mesenchymal stem cells (MSCs).

In ageing and oestrogen-deficient bone marrow, MSCs increasingly differentiate into adipocytes rather than osteoblasts, a process driven in part by PPAR-γ upregulation. Vibration appears to suppress adipogenesis and redirect MSC differentiation toward osteoblastogenesis. Steppe et al. (2020) also confirm this in multiple cell culture models. Sassi (2024), studying osteocyte-cancer cell interactions, further demonstrates that vibration-stimulated osteocytes alter their secretory profiles in ways that change their cellular environment which is consistent with the notion that osteocytes are active regulators of bone marrow biology instead of passive bystanders.

4.5 The LINC complex and cytoskeletal mechanotransduction

Olçum et al. (2016) describe the role of the LINC complex (Linker of Nucleoskeleton and Cytoskeleton) as an internal mechanical amplification mechanism: low-magnitude external vibration is amplified within cells through cytoskeletal remodeling, allowing signals that appear too weak to generate significant bone strain to trigger intracellular signaling cascades. This mechanism explains the apparent paradox that low-magnitude vibration (0.1–0.3 g notably lower than the habitual physical activity loads) can produce measurable osteogenic effects.

5. Limitations and gaps in the literature

5.1 Extreme protocol heterogeneity

As documented throughout this review, the vibration therapy literature is characterised by a high protocol heterogeneity across essentially every parameter: frequency (8–90 Hz), magnitude (0.1–12 g), session duration (1–60 min), session frequency (2/week up to daily), platform type (synchronous vs. side-alternating; standing vs. wearable), posture during vibration (static vs. Exercising, or the angle knee), and total intervention duration (4 weeks to 22 months).

This makes cross-study comparison unreliable and meta-analytic pooling problematic, as Fratini et al. (2016) and Oliveira et al. (2016) demonstrate. Without consensus protocol standards, the field cannot determine optimal parameters or make clear and reliable clinical recommendations.

5.2 DXA insensitivity as a measurement limitation

DXA measures BMD: a two-dimensional projection of a three-dimensional structure; and is relatively insensitive to changes in bone microarchitecture, trabecular connectivity, cortical thickness, and bone stiffness. Multiple studies in this review (Bilek et al., 2024,DadeMatthews et al., 2022,Rajapakse et al., 2021) demonstrate that vibration therapy can produce significant improvements in bone quality metrics detectable by MRI, CT, or BCT while showing no significant DXA changes.

This means the field might be repeatedly underestimating the efficacy of vibration by relying on the wrong measurement tool. Future studies should make more use of pQCT, HR-pQCT, or BCT as primary or co-primary outcomes.

5.3 Paucity of osteopenia-specific studies

Only a minority of the sources reviewed specifically target osteopenic populations. The majority studied osteoporosis or mixed populations troughout the T-score values. This means that most evidence for vibration therapy's effects on osteopenia is extrapolated from adjacent populations. Given that the response to treatment, and the clinical goals differ between osteopenia and osteoporosis (prevention of progression vs. fracture prevention and reversal), further dedicated osteopenia studies are needed.

Marini et al. (2021) make this point starkly: their systematic review of combined physical-pharmacological treatment in osteopenia and osteoporosis found only a single eligible RCT in the world literature.

5.4 Underrepresentation of men

Men are profoundly underrepresented across the corpus, comprising a small fraction of study participants in most reviews and being entirely excluded from many trials. Given that men do develop osteopenia and osteoporosis (at lower rates but with potentially higher fracture mortality), and that secondary causes (hypogonadism, corticosteroid use) are common, this represents a significant evidence gap.

5.5 Short intervention durations and follow-up periods

Many studies in the reviewed literature used intervention durations of 12 weeks to 6 months which is potentially insufficient for the bone remodeling cycle which takes usually around 3–6 months per cycle to produce detectable BMD changes.

Massini et al. (2025) find that protocols of less than 18 weeks are most probably insufficient. Li et al. (2024) observe that significant BMD effects at 6 months were not sustained at 12 months, though this may reflect a treatment plateau rather than reversal. Long-term follow-up (more than 2 years) and durability of effect data remain scarce.

5.6 Small sample sizes and statistical power

Many individual RCTs lack the necessary evaluation procedures to detect the small BMD effect sizes expected from vibration therapy. Massini et al. (2025) note that low certainty of evidence at the femoral neck and lumbar spine is partly attributable to small sample sizes across individual studies. The largest meta-analyses (de Oliveira et al., 2022, Zhang et al., 2022) obtain partial results through aggregation of data, but the methodological quality of primary studies still remains variable.

5.7 Adverse effects and long-term safety

The short-term safety profile of low-magnitude vibration therapy is well-supported: de Oliveira et al. (2022) report an adverse event rate of only 2.8% across 2,089 participants. Furthermore, no serious adverse events were reported in the 15 systematic reviews included in Yin et al. (2024). However, high-magnitude WBV (≥1 g) in osteopenic or osteoporotic individuals is explicitly cautioned against by de Oliveira et al. (2022) due to fracture risk.

6. Clinical implications and recommendations

6.1 Evidence-based protocol parameters

Based on the data obtained in this review, the following vibration therapy parameters are best supported for osteopenic patients seeking bone density maintenance or modest improvement. It must be noted that exercising during vibration sessions appears to reduce osteogenic efficacy compared to static standing (Fratini et al., 2016), though combined vibration-exercise programs may better address the functional and neuromuscular goals of osteopenia management.These are presented as a practical reference and should be individualised based on patient characteristics.

Table 2. Relevant vibration therapy parameters

Study	**Frequency**	**Magnitude**	**Session**	**Duration**	**Platform**
Rajapakse (2021)	30 Hz	0.3 g	10 min/day	12 months	Standing, feet
Beck / VIBMOR (2022)	30 Hz	0.4 g	10 min/day	9 months	Standing, feet
Qin / VIBE (2019)	30 Hz	0.3 g	10 min/day	90 days	Supine, feet
Tan (2016)	35 Hz	0.25 g	15 min/day	4 weeks	Standing, feet
Bilek / Osteoboost (2024)	20–40 Hz	0.1–0.3 g	30 min/day	12 months	Wearable belt
Dutra (2016)	60 Hz	0.6 g (<1mm)	20 min/day	12 months	Vertical platform
Sen (2020)	30–40 Hz	2–4 mm amp.	Not specified	6 months	WBV platform
He (2022)	8–10 Hz	2 mm amp.	5 min, 2×/wk	24 weeks	WBV platform
Kienberger (2022)	18–20 Hz	2 mm amp.	~6 min, 2×/wk	12 months	Galileo, side-alt.

6.2 Target population and timing

The strongest evidence for vibration therapy effectiveness is in postmenopausal women aged 50–65 which is the population experiencing the highest bone loss rate and greatest potential for BMD modification. The evidence for the >65 age group is more equivocal, and both Marín-Cascales et al. (2018) and Tan et al. (2016) identify diminished osteogenic response after this threshold. However, functional benefits such as strength, balance and the reduction of fall risk are consistently demonstrated across all age groups, making vibration therapy an acceptable intervention in older cohorts even if BMD gains are not the main target.

Patients with lower BMD within the osteopenic range may respond better, given the inverse relationship between baseline BMD and vibration response (Fratini et al., 2016; Rajapakse et al., 2021). Body weight should also be considered: de Oliveira et al. (2022) find that women under 65 kg show greater lumbar spine BMD responses.

6.3 Use of DXA vs. advanced imaging for monitoring

In light of DXA's demonstrated insensitivity to the microstructural benefits of vibration therapy (Bilek et al., 2024, Rajapakse et al., 2021;), clinicians and researchers monitoring patients receiving vibration therapy should consider supplementing annual DXA with bone quality assessments where feasible, including vertebral fracture assessment, FRAX score updates, and, where available, pQCT or CT-based bone strength measures. Absence of DXA improvement does not rule out clinically meaningful bone quality benefits.

6.4 Safety considerations

Low-magnitude vibration therapy (≤0.3–0.4 g) delivered through the feet via standing platforms or wearable devices has an excellent short-term safety profile across multiple large studies. Key safety considerations include: avoiding high-magnitude protocols (>1 g) in osteopenic and osteoporotic patients due to fracture risk.

On the same note, ensuring appropriate posture during vibration sessions (such as semi-flexed knees preferred over fully extended), screening for contraindications (e.g. recent fractures, implanted hardware, active deep vein thrombosis, and severe inner ear disorders) and using frequencies ≤50 Hz in frail or elderly populations, are alo important, given that Massini et all's (2025) cautions against higher frequencies which increase adverse event risk.

6.5 Priorities for future research

This review identifies the following as important areas for future research in vibration therapy for osteopenia:

- Dedicated RCTs in osteopenic (not osteoporotic) populations, with sufficient sample size and duration (≥12 months) to detect BMD effects with adequate power
- Male-specific trials and sub-group analyses in mixed-sex studies, given the current near-total absence of male data
- Protocol standardisation studies comparing frequency x magnitude x duration combinations systematically in controlled designs
- Use of advanced imaging (HR-pQCT, BCT, MRI) as primary or co-primary outcomes alongside DXA
- Biomarker studies with standardised timing protocols to resolve the apparent disconnect between structural and biochemical markers of bone response
- Long-term studies (≥24 months) examining durability of effect and optimal maintenance protocols after initial benefit is achieved
- Studies combining targeted axial vibration (wearable devices) with pharmacological agents in osteopenic populations

3. Conclusions

This narrative review, synthesising 40 sources on vibration therapy and bone pathology, supports a relatively optimistic assessment of vibration therapy's role in osteopenia management. The evidence is strongest for three main conclusions:

The first one, that low-magnitude vibration therapy (approximately 30 Hz, 0.3 g) applied axially through the lower limbs has the highest-quality evidence for BMD stabilisation and modest improvement in postmenopausal women; The second is that functional benefits such as muscle strength, balance, fall risk reduction are more consistent and robust than BMD effects and are clinically important. The third one is that the OsteoBoost wearable belt, now FDA-cleared specifically for osteopenia, represents a significant clinical advance in targeted axial vibration delivery and suggests a future direction for non-platform vibration therapy.

Key limitations that temper these conclusions include the protocol variety across studies, DXA's technical insensitivity to microstructural improvements, the lack of dedicated osteopenia studies, the near-total absence of male-specific evidence, and the short duration of most trials. These limitations mean that the current evidence, while promising, does not yet support a definite clinical recommendation of vibration therapy as a primary treatment of osteopenia

The prospects are encouraging. The development of wearable axial vibration devices, the increasign number of meta-analyses on low-magnitude protocols, the growing mechanistic understanding of osteocyte and MSC biology under vibration, and the consistent demonstration of functional benefits across diverse populations all point toward a possible clinically viable modality that requires continued investigation and, in specific clinical contexts, implementation under supervision.

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