



Neurophysiological assessment of bone mechanosensitivity using the bone myoregulation reflex

Tuğba Aydın^{1,2} · Nilgün Yıldız⁴ · Aybike Ata¹ · Eser Kalaoglu¹ · Selim Sezikli¹ · Mert Çetin¹ · Nida Lale Köksal¹ · Kadriye Öneş^{1,2} · Halime Kibar¹ · Kemal Sitki Türker³ · İlhan Karacan^{1,2}

Received: 12 August 2025 / Accepted: 3 October 2025

© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2025

Abstract

Background Mechanical loading is essential for bone growth, development, and skeletal integrity, and these effects are mediated primarily by osteocytes, the principal mechanosensory cells of bone. Aging and osteoporosis can impair osteocytes and the lacunocanalicular system, leading to bone loss, reduced biomechanical quality, and increased fragility. The bone myoregulation reflex may offer a noninvasive means of evaluating bone mechanosensitivity and quality.

Objectives This study aimed to evaluate the applicability of a noninvasive neurophysiological method based on the bone myoregulation reflex as a tool for determining bone mechanosensitivity and quality.

Methods The mechanical threshold was defined as the minimum force required to activate osteocytes, which are the sensory receptors of the bone myoregulation reflex, and was estimated using a cumulative averaging method. Thresholds were measured first in healthy young adults during whole-body vibration and then in older adults with primary osteoporosis to assess the ability of the method to detect bone loss-related changes in mechanosensitivity.

Results In healthy young adults, the normalized mechanical thresholds ranged from 2.9 to 4.7% of the peak-to-peak vibration loading force, depending on the vibration frequency. In contrast, participants with osteoporosis exhibited significantly higher thresholds, ranging from 9.0 to 15.5%.

Conclusion This proof-of-concept study demonstrates the feasibility of a neurophysiological method for assessing bone mechanosensitivity using the bone myoregulation reflex. The higher thresholds observed in patients with osteoporosis suggest impaired osteocyte function and provide a basis for future clinical validation. Such validation should consider BMI and sex and include both young and older non-osteoporotic controls to distinguish osteoporosis from age-related effects.

Communicated by William J. Kraemer.

✉ Tuğba Aydın
drtugbaaydin@gmail.com

Nilgün Yıldız
nilgyildiz@gelisim.edu.tr

Aybike Ata
draybikeata@gmail.com

Eser Kalaoglu
eserkalaoglu@hotmail.com

Selim Sezikli
selimsezikli@hotmail.com

Mert Çetin
drmertcetin@gmail.com

Nida Lale Köksal
nidale9@gmail.com

Kadriye Öneş
kadriyeones@yahoo.com

Halime Kibar
halimekibar22@gmail.com

Kemal Sitki Türker
turker.77@gmail.com

İlhan Karacan
mdkaracanilhan@gmail.com

¹ Physical Therapy and Rehabilitation Department, Istanbul Physical Therapy Rehabilitation Training and Research Hospital, Adnan Kahveci Bulvarı No. 145, 34186 Bahçelievler/Istanbul, Turkey

² Hamidiye Faculty of Medicine, Physical Medicine and Rehabilitation Department, Health Sciences University, Istanbul, Turkey

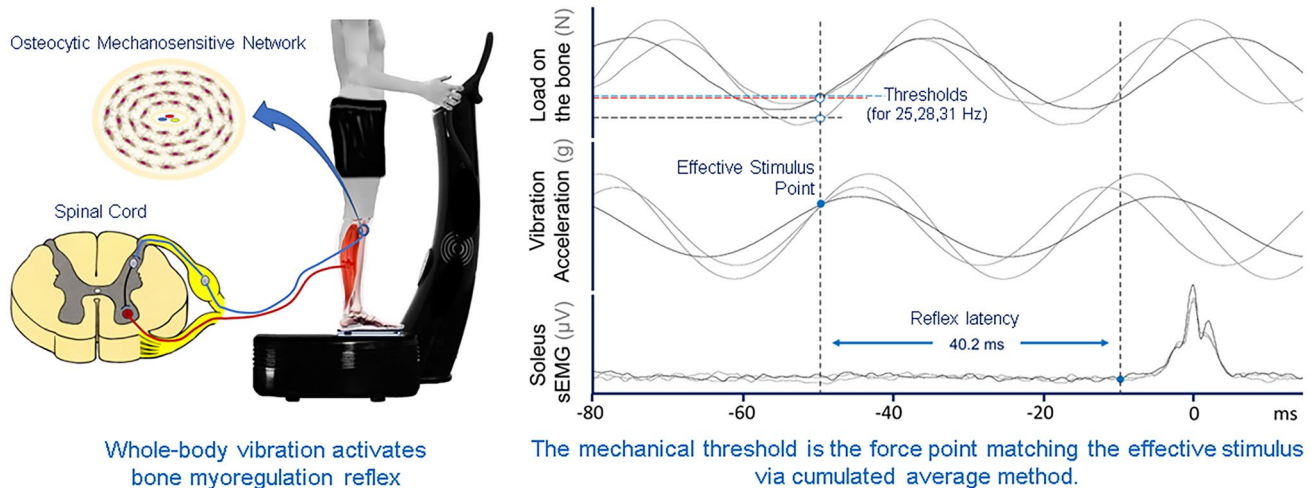
³ Faculty of Dentistry, Physiology Department, İstanbul Gelisim University, Avcılar, Istanbul, Turkey

⁴ Faculty of Health Sciences, Department of Physiotherapy and Rehabilitation, İstanbul Gelişim University, İSTANBUL, Türkiye

Graphical abstract

Bone Mechanical Threshold Estimation

- ✓ Evaluating the bone myoregulation reflex may aid in assessing bone's mechanical behavior in vivo
- ✓ The cumulated average analysis indicates higher mechanical thresholds in osteoporotic patients



Keywords Osteocytes · Mechanotransduction · Vibration · Mechanical loading · Functional skeletal adaptation

Abbreviations

CI	Confidence interval
BMR	Bone myoregulation reflex
LCS	Lacunocanalicular system
EST	Effective stimulus time
MT	Mechanical threshold
MTbw	Mechanical threshold normalized to body weight
MTpp	Mechanical threshold normalized to the peak-to-peak amplitude
PP	Peak-to-peak
SD	Standard deviation
sEMG	Surface electromyography
WBV	Whole-body vibration

Introduction

Physical activity and exercise are widely recognized as primary strategies for supporting skeletal development and maximizing bone mass in children and adolescents (Cartledge et al. 2022). They also serve as effective adjunctive treatments for managing osteoporosis (Gregson et al. 2022) and play important roles in facilitating bone fracture healing (Zhang et al. 2017). In particular, weight-bearing exercises are effective for improving bone health, with strong evidence supporting their role in increasing bone density (Gregson

et al. 2022; Ishikawa et al. 2013; Zhang et al. 2017). These effects are consistent with Wolff's law and Frost's Utah paradigm, which suggest that bones adapt to mechanical loads, resulting in increased strength (Frost 1998; Wolff 1986).

The structural integrity of bone depends primarily on the mechanical stimuli sensed by osteocytes, the principal mechanosensory cells in bone (Goggin et al. 2016; Pearson and Lieberman 2004; Rolvien et al. 2020). This role is facilitated by the osteocytic lacunocanalicular system (LCS), which acts as a stress concentrator and amplifies macroscopic strain in the bone by up to 100-fold; this amplification is further modulated by the material properties of the surrounding peri-lacunar tissue (Goggin et al. 2016; You et al. 2001). With aging, osteocytes and the associated lacunocanalicular system undergo structural and functional deterioration, particularly in individuals with osteoporosis, leading to bone loss. Consequently, the biomechanical quality of bone decreases, and its fragility increases (Gregson et al. 2022; Javaheri and Pitsillides 2019; Karacan and Türker 2024). However, assessing this loss of biomechanical quality in vivo remains a significant challenge.

The bone myoregulation reflex (BMR) may offer new opportunities to address this gap. The BMR is a conceptual framework that describes a possible neuromechanical feedback loop between bone and skeletal muscle. Mechanical loading of bone is known to activate the osteocytic

network within the mineralized matrix, which functions as a mechanosensitive receptor (Karacan and Türker 2024). In the BMR model, these signals can be conveyed to the spinal cord via thick myelinated afferent fibers—possibly A β fibers—and relayed to skeletal muscles through alpha motor neurons, potentially contributing to reflexive muscle regulation (Cakar et al. 2015; Corum et al. 2022; Kalaoglu et al. 2023; Karacan et al. 2009, 2017; Karacan and Türker 2024; Yildirim et al. 2020). The BMR could thus enable the in vivo evaluation of osteocyte mechanosensitivity and facilitate determination of the bone's mechanical threshold.

This study was based on the hypothesis that a reduction in mechanosensitivity—detected by comparing the mechanosensitivity of individuals with osteoporosis with that of healthy controls—can be identified via the BMR. If validated, this approach could provide a noninvasive neurophysiological method for assessing the biomechanical properties and strength of bone through mechanosensitivity.

Methods

The study protocol was approved by the local ethics committee (Bakırköy Dr. Sadi Konuk Training and Research Hospital, Clinical Research Ethics Committee; Approval No.: 2023/321) and was conducted in accordance with the principles of the Declaration of Helsinki. All participants provided written informed consent prior to participation. The study protocol was registered with ClinicalTrials.gov (NCT06017245).

Participants

The study included 30 healthy adults (14 females, 16 males) aged 20–40 years and 39 patients with primary osteoporosis (31 females, 8 males) aged 50–80 years. The exclusion criteria included the presence of scars, dermatitis, or other dermatological conditions at the surface electromyography (sEMG) electrode placement site; a history of kidney stones; and intolerance to whole-body vibration (WBV) during the familiarization protocol.

Osteoporosis was diagnosed according to the criteria established by the World Health Organization on the basis of bone mineral density measurements obtained by dual-energy X-ray absorptiometry (Kanis 2007). Therefore, participants with a T score ≤ -2.5 for the femoral neck or total hip were classified as having osteoporosis.

The participants in the healthy adult group who completed the study had a mean age of 26.6 ± 2.6 years, a mean height of 174.0 ± 8.8 cm, and a mean body mass index of 24.1 ± 3.4 kg/m². The participants in the osteoporosis group had a mean age of 62.9 ± 7.2 years, a mean height of 159.1 ± 8.8 cm, and a mean body mass index

of 27.1 ± 4.5 kg/m². Their age, height, and body mass index were significantly greater than those of the controls ($p = 0.0001$, $p = 0.0001$, and $p = 0.004$, respectively).

Experimental protocol

Outcome variables

The primary outcome was the mechanical threshold, defined as the minimum loading force generated during WBV that activated osteocytes, the sensory receptors of the BMR. This value was used as an index of bone mechanosensitivity (Fig. 1). WBV delivers a sinusoidal oscillatory force to the participant's body through a vibrating platform. Raw threshold values were expressed in newtons (N) and normalized to both the peak-to-peak amplitude of the loading force signal (MTpp%) and the participant's body weight (MTbw%).

Procedures

The mechanical threshold was determined using the cumulative average method in both healthy young adults and individuals with primary osteoporosis. WBV was applied using a commercial vibration platform (Power Plate® International, Amsterdam, The Netherlands) to activate the BMR. The resulting reflex response from the soleus muscle was recorded using sEMG.

Whole-body vibration The vibration protocol followed methods previously recommended in WBV studies investigating the BMR (Cakar et al. 2015; Kalaoglu et al. 2023; Karacan et al. 2014, 2017; Kilic et al. 2023). Participants stood quietly in an upright posture on the vibration platform and were barefoot, with the feet positioned to ensure equal weight distribution. The knee and ankle joints were kept in a neutral position. For postural stability, participants lightly held the platform's side handles throughout all WBV conditions (Fig. 2). The platform generated linear, vertical oscillations with a 1.25 mm amplitude. WBV was applied at frequencies of 25 Hz, 28 Hz, and 31 Hz, each delivered in randomized order for 30 s to minimize potential order effects, and a 5-s rest interval was provided between trials.

Data recording and analysis sEMG activity was recorded using self-adhesive bipolar Ag/AgCl electrodes (Redline®, Istanbul, Turkey) placed longitudinally over the belly of the right soleus muscle, with an interelectrode distance of 4 cm. A ground electrode was positioned over the right lateral malleolus, following the procedure described by Tucker and Türker (2005). The skin over the recording sites was lightly abraded using fine sandpaper and cleaned with 70% alcohol, and the electrode gel was gently rubbed into the skin. After the gel had dried, self-adhesive pre-gelled Ag/AgCl elec-

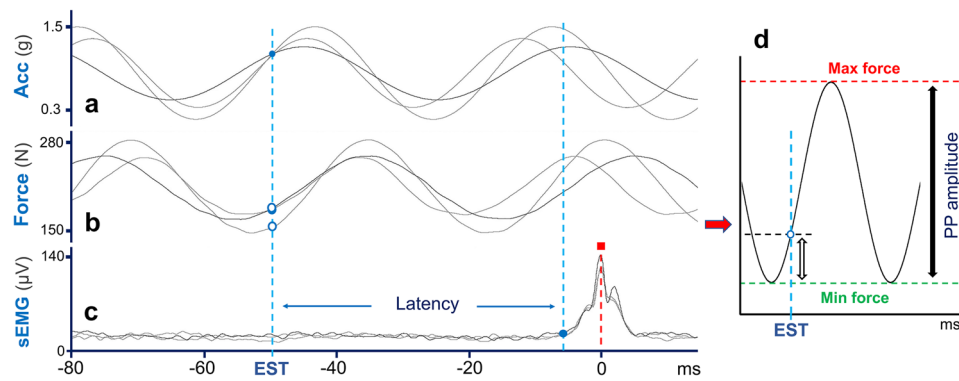


Fig. 1 Measuring BMR latency and mechanical threshold using the cumulative average method. **a** The effective stimulus time (EST) points are represented by solid circles. **b** Mechanical thresholds for each vibration frequency are represented by open circles. **c** The solid square indicates the peak of a spike in the rectified EMG, which is used as the trigger point. These spike peaks serve as triggers to average acceleration, force, and rectified EMG data within a segment

trodes were placed on the skin over the soleus muscle. The same preparation was applied to the ground electrode site. Skin impedance was checked prior to recording to ensure optimal conductivity (≤ 10 k Ω).

sEMG, accelerometer, and force signals were recorded simultaneously using a data acquisition system (Power1401 MK2, Cambridge Electronic Design Ltd., Cambridge, UK) at a sampling rate of 20 kHz. All the data were analyzed offline using the Spike2 software package (version 7.20; Cambridge Electronic Design Ltd., Cambridge, UK).

Estimation of BMR latency using the cumulative average method To calculate BMR latency, a piezoelectric accelerometer (LIS344ALH; Ecopack®, Mansfield, TX, USA) mounted on the WBV platform was used in conjunction with sEMG recordings from the right soleus muscle. sEMG signals were bandpass filtered (60–500 Hz), full-wave rectified, and processed for analysis. Peaks in the rectified EMG signal were identified and marked. Spike-triggered averaging was then performed using these EMG peaks as triggers and the acceleration signal as the source. For each vibration frequency, an 80-ms window preceding and a 15-ms window following the trigger were included, and the resulting average acceleration curves were superimposed to generate a cumulative curve. The standard errors of the averaged acceleration signal were calculated for each of the 1600 bins across the time window from –80 ms to +15 ms. The bin with the lowest standard error was defined as the “effective stimulus point” (EST) on the cumulative average acceleration trace (Karacan et al. 2014).

A similar averaging procedure was applied to the sEMG recordings to determine the onset of the BMR response. Reflex latency was calculated as the time interval between

from –80 ms to +15 ms. The solid circle indicates the reflex onset point. **d** A representative averaged force trace for a vibration frequency (28 Hz). The open circle denotes the EST force value, corresponding to the EST point. The mechanical threshold amplitude is indicated by a double-headed open arrow. *Note:* Acc: accelerometer; PP: peak-to-peak

the EST and the EMG-defined onset of the BMR response (Karacan et al. 2014) (Fig. 1a–c).

Estimation of the mechanical threshold using the cumulative average method A load sensor (FC2331-0000-2000L, France) was placed between the participant’s heel and the vibrating platform to record the force signal generated by WBV. Cumulative average curves were generated from simultaneously recorded sEMG, accelerometer, and force signals (Fig. 1a–c). To determine the mechanical threshold, the force magnitude corresponding to the EST on the force trace was identified, and the minimum value of the sinusoidal force curve was subtracted from this magnitude (Fig. 1a–d). This procedure was applied separately for each of the three vibration frequencies.

Statistical analysis

The normality of the data distribution was assessed using the Shapiro–Wilk test. Variables with a normal distribution (age, height, and body mass index) are presented as the mean $\pm$ SD, whereas non-normally distributed variables (raw and normalized mechanical thresholds) are summarized as the median (interquartile range, 25th–75th percentile). Comparisons between two independent groups were performed using the unpaired t test for normally distributed variables and the Mann–Whitney U test for non-normally distributed variables. Statistical significance was defined as $p < 0.05$. Effect sizes for mechanical thresholds were interpreted according to Cohen’s (1988) guidelines: $r = 0.1$ indicates a small effect, $r = 0.3$ a medium effect, and $r = 0.5$ a large effect. The 95% confidence intervals for the mechanical thresholds were calculated using the

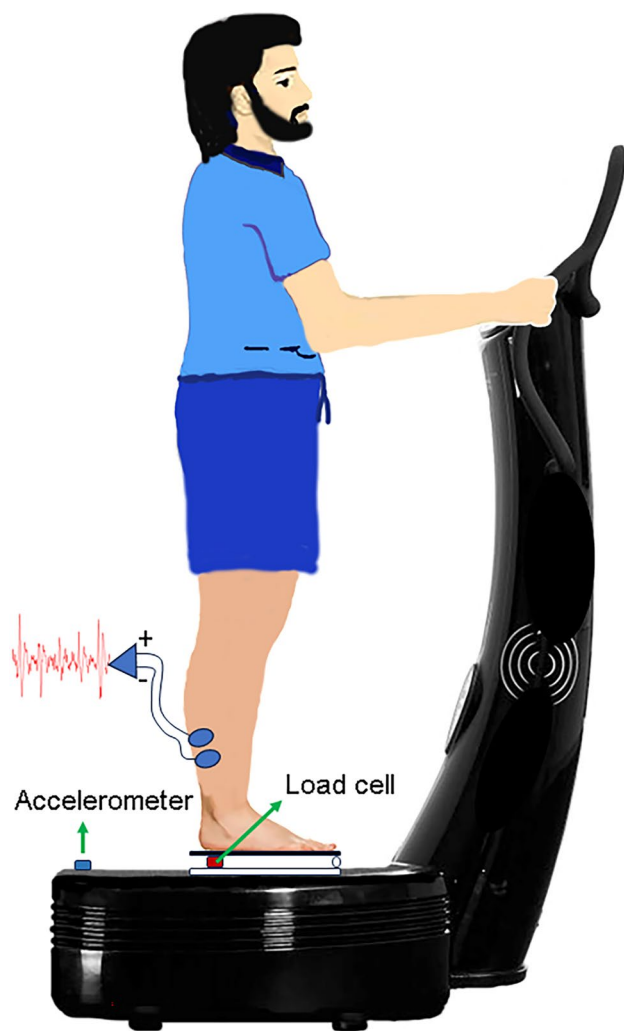


Fig. 2 Experimental setup. An accelerometer mounted on the vibration platform and sEMG electrodes placed on the belly of the soleus muscle were used to measure BMR latency. A load cell positioned between the participant's heel and the platform was used to determine the mechanical threshold

independent-samples Hodges–Lehmann median difference method. All the statistical analyses were conducted using PASW Statistics for Windows, Version 18.0 (SPSS Inc., Armonk, NY, USA).

Results

The raw mechanical thresholds were significantly higher in the osteoporosis group than in the healthy control group (Table 1). In healthy young adults, the mechanical thresholds normalized to the peak-to-peak amplitude of the loading force signal ranged from 2.9 to 4.7%, depending on the vibration frequency. In contrast, the thresholds of individuals with osteoporosis were significantly higher, ranging from 9.0 to 15.5% (Table 2). When normalized to body weight, the mechanical thresholds of the healthy participants ranged from 2.4 to 2.7%, while those of the individuals with osteoporosis ranged from 3.4 to 3.7%, with significant group differences (Table 2).

As illustrated for representative cases (Fig. 1b, d), the mechanical threshold consistently occurred during the ascending phase of the sinusoidal force trace.

Discussion

The BMR is activated by cyclic mechanical loading of bone. The main finding of this study is that the BMR may provide a preliminary neurophysiological means for in vivo assessment of the mechanical threshold at which bone responds to loading. This threshold was significantly higher for individuals with *osteoporosis*, with medium-to-large effect sizes. However, these results should be interpreted with caution given the influence of potential confounders, including age, sex, and BMI, as well as the absence of an age-matched non-osteoporotic control group to distinguish osteoporosis-specific effects from age-related effects.

Rationale and method for determining the bone mechanical threshold via the BMR

Osteocytes, which constitute more than 95% of bone cells in the adult skeleton, form a highly functional and mechanosensitive communication network. These cells are interconnected via dendritic processes that extend through the LCS embedded within the mineralized bone matrix (Dallas et al. 2013; Delgado-Calle and Bellido 2022; Karacan and Türker

Table 1 Raw mechanical thresholds at 25 Hz, 28 Hz, and 31 Hz vibration frequencies

	Healthy young adults ($n=30$)	Osteoporotic group ($n=39$)	Median difference	95% CI		Cohen's r effect size	P value
				Lower	Upper		
Raw MT at 25 Hz (N)	4.9 (2.9–15.9)	17.6 (5.9–39.2)	−3.92	−15.68	−0.01	0.36	0.028
Raw MT at 28 Hz (N)	4.9 (2.9–10.8)	10.8 (3.4–40.2)	−2.94	−8.82	−0.01	0.34	0.046
Raw MT at 31 Hz (N)	2.9 (2.0–8.6)	7.8 (4.9–41.2)	−3.92	−6.86	−0.98	0.41	0.009

Values are presented as medians (interquartile ranges, 25th–75th percentiles)

Table 2 Normalized mechanical thresholds measured at 25 Hz, 28 Hz, and 31 Hz vibration frequencies

	Healthy young adults (<i>n</i> = 30)	Osteoporotic group (<i>n</i> = 39)	Median difference	95% CI		Cohen's <i>r</i> effect size	<i>P</i> value
				Lower	Upper		
MTbw% at 25 Hz	0.6 (0.4–1.9)	2.9 (0.8–6.1)	−0.64	−277	−0.15	0.39	0.015
MTbw% at 28 Hz	0.6 (0.4–1.6)	1.8 (0.6–6.7)	−0.58	−1.59	−0.02	0.35	0.040
MTbw% at 31 Hz	0.5 (0.3–1.4)	1.1 (0.8–6.6)	−0.54	−1.36	−0.17	0.42	0.007
MTpp% at 25 Hz	4.7 (2.6–11.1)	15.5 (5.6–45.3)	−4.92	−19.44	−1.87	0.46	0.003
MTpp% at 28 Hz	4.5 (2.3–14.7)	11.7 (4.8–56.0)	−4.95	−11.66	−1.25	0.43	0.007
MTpp% at 31 Hz	2.9 (1.8–8.8)	9.0 (5.7–59.5)	−4.94	−9.14	−2.21	0.47	0.002

MTbw%: Mechanical threshold as % of baseline width

MTpp%: Mechanical threshold as % of peak-to-peak vibration amplitude;

Values are presented as medians (interquartile ranges, 25th–75th percentiles)

2024; Rolvien et al. 2020). Mechanical loading (stress) induces deformation (strain) in the bone matrix, generating a pressure gradient that drives the flow of interstitial fluid throughout this network. The resulting fluid movement stimulates mechanoreceptors on osteocyte membranes through two principal mechanisms: strain-generated potentials and fluid flow shear stress (Dallas et al. 2013; Kao et al. 2019; Karacan and Türker 2024; Lai et al. 2015). The osteocytic network, which is embedded in the bone matrix, thus functions as the receptor system for the BMR (Karacan and Türker 2024). Because the BMR originates from osteocyte-mediated mechanosensing, the minimum force required to evoke this reflex can serve as a direct in vivo indicator of the bone's mechanical threshold.

Mechanistic interpretation of elevated thresholds

The elevated mechanical thresholds observed in individuals with osteoporosis are consistent with structural and functional deterioration of osteocytes and the LCS, including reduced osteocyte density, loss of dendritic connectivity, expansion of lacunocanalicular fluid spaces, and micropetrosis, all of which compromise mechanotransduction. These impairments likely reduce the mechanosensitivity of osteocytes and disrupt the stress-concentrating and strain-amplifying functions of the LCS, thereby increasing the mechanical threshold (Gregson et al. 2022; Javaheri and Pitsillides 2019; Karacan and Türker 2024). However, alternative contributors should also be considered. Age-related neuromuscular changes, including reductions in sensory nerve fiber density; motor neuron degeneration; diminished regenerative capacity; and decreases in axonal number, diameter, and internodal length with concomitant slowing of conduction velocity, as well as structural alterations at the neuromuscular junction, may impair reflex responsiveness and proprioceptive feedback (Karacan and Türker 2024). Research directly addressing the effects of age-related neuromuscular changes on the reflex thresholds of any receptor, including

osteocytes, is scarce. The only available data come from muscle spindle-mediated responses; Lin and Sabbahi (1998) reported that the threshold velocity of the stretch reflex does not change with aging, although the reflex response is diminished in magnitude and prolonged in latency. Taken together, the evidence indicates that the elevated mechanical thresholds observed in osteoporosis can most plausibly be attributed to osteocyte and LCS deterioration, while the potential influence of age-related neuromuscular changes, although less likely, should not be dismissed.

Methodological considerations

WBV is a weight-bearing exercise technique that delivers controlled mechanical loading to the bone and facilitates experimental measurements, because the subject remains in a fixed position. Despite these advantages, measuring the latency of reflex responses (e.g., BMR) induced by WBV remains a significant challenge in vibration experiments. For the soleus tendon reflex triggered by a reflex hammer, determining the mechanical stimulus onset time and measuring latency are relatively straightforward. However, WBV generates high-frequency sinusoidal mechanical stimuli with continuously fluctuating intensity. For such mechanical stimuli, the reflex response trigger time (i.e., effective stimulus time or EST) cannot be determined using conventional methods. This challenge was effectively addressed by the use of the cumulative average method, which has been shown to be highly reliable (Karacan et al. 2014; Kilic et al. 2023). The reported intraclass correlation coefficient for estimating the EST was 0.988, with a precision error of 1.3% (Kilic et al. 2023).

In the present study, WBV was applied at frequencies generating accelerations between 0.3 and 1.5 *g*. As a result, the force (stress) transmitted to the participant's heel fluctuated continuously throughout the vibration period (Fig. 1b). This force was recorded using a compression load cell positioned between the participant's heel and the vibration

platform (Fig. 2). The cumulative average method was then used to estimate the mechanical threshold, as illustrated in Fig. 1. In this study, the effective stimulation time (EST), i.e., the moment when the BMR response occurred, was considered an indicator of the minimum loading force threshold required to activate the BMR. As shown in Fig. 1a, the effective stimulation time point, defined as the moment when mechanical loading activated the osteocytic network, could be identified in the accelerometer recordings. In Fig. 1b, the corresponding points on the force traces (indicated by open circles) reveal the mechanical threshold for each vibration frequency.

To determine the mechanical threshold, two cohorts were formed: healthy young adults and individuals with primary osteoporosis. Bone density and quality, together with osteocyte and LCS functionality, peak in young adulthood and progressively decline with age. In primary osteoporosis, bone loss is additionally associated with the deterioration of osteocyte function and LCS architecture. To examine how the mechanical threshold changes with bone loss, measurements were performed in both groups. This cohort design followed the framework recommended by the World Health Organization for the diagnosis and classification of primary osteoporosis, in which deviations in bone density among older individuals are evaluated relative to those among healthy young adults (Kanis 2007). Accordingly, the mechanical threshold of the BMR was compared between older adults with primary osteoporosis and healthy young adults.

According to Newton's second law (force = mass $\times$ acceleration) (Newton 1687), the magnitude of loading force depends on both body mass and the intensity of acceleration generated by WBV. To account for interindividual variability, thresholds were first normalized to body mass, but this adjustment provided only minimal gains in sensitivity, with effect sizes remaining in the medium range (Cohen's $r=0.35\text{--}0.42$). In contrast, normalization to the peak-to-peak amplitude of the loading force resulted in clearer group separation, with effect sizes in the medium-to-large range (Cohen's $r=0.43\text{--}0.47$). Collectively, these findings demonstrate that peak-to-peak amplitude normalization yields a more sensitive and physiologically meaningful index of impaired mechanosensitivity in osteoporosis.

Study limitations

Several limitations should be acknowledged. Although the BMR was employed to assess the mechanical threshold, with osteocytes considered the primary mechanosensory receptors, age-related changes in neural pathways and at the neuromuscular junction may also have contributed to the measured thresholds. The lack of a control group consisting of older individuals without osteoporosis limits the ability

to separate the effects of aging from those of osteoporosis. However, we used the approach recommended by the World Health Organization, as detailed in the Discussion. Furthermore, while a potential influence of sex cannot be excluded, no study has, to our knowledge, demonstrated differences in osteocyte mechanosensitivity between healthy subjects of different sexes. Sex should nonetheless be considered a potential confounder in future research.

Conclusion

This proof-of-concept study demonstrates the feasibility of a BMR-based neurophysiological method for assessing bone mechanosensitivity, revealing elevated thresholds in individuals with primary osteoporosis. These findings suggest that BMR-based, noninvasive assessment may have clinical relevance for detecting alterations in bone mechanosensitivity. Moreover, in vivo neurophysiological evaluation of the biomechanical properties of bone could offer a practical framework for individualized, threshold-based exercise interventions.

Future research should focus on formal validation of this method, including test–retest reliability, benchmarking against established bone assessment techniques, and determination of the minimal detectable change. Such work, ideally conducted in sex-matched cohorts that include both young adults and older non-osteoporotic controls, will be essential for establishing accuracy, reproducibility, and diagnostic value before clinical translation.

Acknowledgements The authors would like to express their sincere gratitude to the physical therapy and rehabilitation residents who voluntarily participated in the study.

Author contributions The experiments were conducted at the Research Laboratory of Istanbul Physical Medicine and Rehabilitation Training and Research Hospital. KST and IK: conceptualization, methodology, resources, formal analysis, investigation, writing—original draft, writing—review & editing, and supervision; TA, NY: conceptualization, methodology, resources, data curation, validation, investigation, and writing—original draft; EK, MC, and AA: conceptualization, methodology, resources, investigation, writing—original draft, and visualization; SS, NLK, and KO: conceptualization, methodology, resources, investigation, and writing—original draft.

Funding None declared.

Data availability All the raw and processed data supporting the findings of this study, including mechanical threshold measurements, EMG recordings, and vibration force traces, are available in CSV format from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors have not disclosed any competing interests.

References

- Cakar HI, Cidem M, Sebik O, Yilmaz G, Karamehmetoglu SS, Kara S, Karacan I, Türker KS (2015) Whole-body vibration-induced muscular reflex: is it a stretch-induced reflex? *J Phys Ther Sci* 27:2279–2284. <https://doi.org/10.1589/jpts.27.2279>
- Cartledge TJ, Murphy J, Foster CE, Tibbitts B (2022) The effect of weight-bearing exercise on the mechanisms of bone health in young females: a systematic review. *J Frailty Sarcopenia Falls* 7:231–250. <https://doi.org/10.22540/JFSF-07-231>
- Cohen J (1988) Statistical power analysis for the behavioral sciences, 2nd edn. Lawrence Erlbaum Associates, Hillsdale, NJ
- Corum M, Topkara B, Kokce M, Özkan M, Bucak OF, Aytüre L, Karacan I, Türker KS (2022) The reflex mechanism underlying the neuromuscular effects of whole-body vibration: is it the tonic vibration reflex? *J Musculoskelet Neuronal Interact* 22:37–42
- Dallas SL, Prideaux M, Bonewald LF (2013) The osteocyte: an endocrine cell ... and more. *Endocr Rev* 34:658–690. <https://doi.org/10.1210/er.2012-1026>
- Delgado-Calle J, Bellido T (2022) The osteocyte as a signaling cell. *Physiol Rev* 102:379–410. <https://doi.org/10.1152/physrev.00043.2020>
- Frost HM (1998) Changing concepts in skeletal physiology: Wolff's Law, the Mechanostat, and the "Utah Paradigm." *Am J Hum Biol* 10:599–605. [https://doi.org/10.1002/\(SICI\)1520-6300\(1998\)10:5%3c599::AID-AJHB6%3e3.0.CO;2-9](https://doi.org/10.1002/(SICI)1520-6300(1998)10:5%3c599::AID-AJHB6%3e3.0.CO;2-9)
- Goggins PM, Zygalakis KC, Oreffo RO, Schneider P (2016) High-resolution 3D imaging of osteocytes and computational modelling in mechanobiology: insights on bone development, ageing, health and disease. *Eur Cells Mater* 31:264–295. <https://doi.org/10.22203/ecm.v031a18>
- Gregson CL, Armstrong DJ, Bowden J et al (2022) UK clinical guideline for the prevention and treatment of osteoporosis. *Arch Osteoporos* 17:80. <https://doi.org/10.1007/s11657-022-01115-8>
- Ishikawa S, Kim Y, Kang M, Morgan DW (2013) Effects of weight-bearing exercise on bone health in girls: a meta-analysis. *Sports Med* 43:875–892. <https://doi.org/10.1007/s40279-013-0060-y>
- Javaheri B, Pitsillides AA (2019) Aging and mechanoadaptive responsiveness of bone. *Curr Osteoporos Rep* 17:560–569. <https://doi.org/10.1007/s11914-019-00553-7>
- Kalaoglu E, Faruk Bucak O, Kökçe M, Ozkan M, Çetin M, Atasoy M, Aytüre L, Karacan I (2023) High-frequency whole-body vibration activates tonic vibration reflex. *Turk J Phys Med Rehabil* 69:46–51. <https://doi.org/10.5606/tftrd.2023.10854>
- Kanis JA (2007) Assessment of osteoporosis at the primary health care level. Technical Report, World Health Organization Collaborating Centre for Metabolic Bone Diseases, University of Sheffield, Sheffield
- Kao FC, Chiu PY, Tsai TT, Lin ZH (2019) The application of nanogenerators and piezoelectricity in osteogenesis. *Sci Technol Adv Mater* 20:1103–1117. <https://doi.org/10.1080/14686996.2019.1693880>
- Karacan I, Türker KS (2024) Exploring neuronal mechanisms of osteosarcopenia in older adults. *J Physiol*. <https://doi.org/10.1113/JP285666>
- Karacan I, Sariyildiz MA, Ergin Ö, Ozen A, Karamehmetoglu SS (2009) Bone myoregulation reflex: a possible new mechanism. *Nobel Med* 5(3):9–17
- Karacan I, Cakar HI, Sebik O, Yilmaz G, Cidem M, Kara S, Türker KS (2014) A new method to determine reflex latency induced by high rate stimulation of the nervous system. *Front Hum Neurosci* 8:536. <https://doi.org/10.3389/fnhum.2014.00536>
- Karacan I, Cidem M, Türker KS (2017) Whole-body vibration induces distinct reflex patterns in human soleus muscle. *J Electromyogr Kinesiol* 34:93–101. <https://doi.org/10.1016/j.jelekin.2017.04.007>
- Kilic A, Soytürk G, Karaoglu A, Topkara Arslan B, Karacan I, Türker KS (2023) A reliability study on the cumulative averaging method for estimating effective stimulus time in vibration studies. *J Electromyogr Kinesiol* 70:102768. <https://doi.org/10.1016/j.jelekin.2023.102768>
- Lai X, Price C, Modla S, Thompson WR, Caplan J, Kirn-Safran CB, Wang L (2015) The dependences of osteocyte network on bone compartment, age, and disease. *Bone Res* 3:15009. <https://doi.org/10.1038/boneres.2015.9>
- Lin FM, Sabbahi M (1998) The aging effects on the EMG and mechanical responses of the human wrist flexor stretch reflexes. *Electromyogr Clin Neurophysiol* 38:323–332
- Newton I (1687) *Philosophiæ Naturalis Principia Mathematica*. <https://web.math.princeton.edu/~eprywes/F22FRS/newtonprincipia.pdf>
- Pearson OM, Lieberman DE (2004) The aging of Wolff's "law": ontogeny and responses to mechanical loading in cortical bone. *Am J Phys Anthropol Suppl* 39:63–99. <https://doi.org/10.1002/ajpa.20155>
- Rolvien T, Milovanovic P, Schmidt FN, von Kroge S, Wölfel EM, Krause M, Wulff B, Püschel K, Ritchie RO, Amling M, Busse B (2020) Long-term immobilization in elderly females causes a specific pattern of cortical bone and osteocyte deterioration. *J Bone Miner Res* 35:1343–1351. <https://doi.org/10.1002/jbmr.3970>
- Tucker KJ, Türker KS (2005) A new method to estimate signal cancellation in the human maximal M-wave. *J Neurosci Methods* 149:31–41. <https://doi.org/10.1016/j.jneumeth.2005.05.010>
- Wolff J (1986) The law of bone remodelling. Springer, pp 23–74
- Yildirim MA, Topkara B, Aydın T, Paker N, Soy D, Coskun E, Ones K, Bardak A, Kesiktas N, Ozyurt MG, Celik B, Onder B, Kılıc A, Kucuk HC, Karacan I, Türker KS (2020) Exploring the receptor origin of vibration-induced reflexes. *Spinal Cord* 58(6):716–723. <https://doi.org/10.1038/s41393-020-0419-5>
- You L, Cowin SC, Schaffler MB, Weinbaum S (2001) A model for strain amplification in the actin cytoskeleton of osteocytes due to fluid drag. *J Biomech* 34(11):1375–1386. [https://doi.org/10.1016/S0021-9290\(01\)00107-5](https://doi.org/10.1016/S0021-9290(01)00107-5)
- Zhang L, Miramini S, Richardson M, Ebeling P, Little D, Yang Y, Huang Z (2017) Computational modelling of bone fracture healing under partial weight-bearing exercise. *Med Eng Phys* 42:65–72. <https://doi.org/10.1016/j.medengphy.2017.01.025>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.