https://doi.org/10.48047/AFJBS.6.16.2024.4093-4100

African Journal of Biological Sciences

Journal homepage: http://www.afjbs.com

Research Paper Open Access

Comparative Study of Bone Density in Healthy, Fractured, and Decomposed Bones: Implications for Orthopedic Treatments and Forensic investigations

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Received: 06 Sep, 2024
Accepted: 05 Dec, 2024
Published: 21 Dec, 2024
doi:10.48047/AFJBS.6.16.2024.4093-4100

ABSTRACT

Background: Bone mineral density and structural integrity are critical in orthopedic treatments and forensic investigations. Changes in bone characteristics due to fractures and decomposition affect clinical management and post-mortem analysis. Understanding these variations is essential for improving fracture care and forensic identification techniques. This study compares bone mineral density and structural properties among healthy, fractured, and decomposed bones, analyzing their implications for medical and forensic applications.

Methods: A study was conducted at Kabir Medical College Department of Forensic Medicine, Gandhara University Peshawar. Total of 92 bone samples were analyzed and categorized into three groups: healthy (n = 30), fractured (n = 32), and decomposed (n = 30). Bone mineral density, cortical thickness, trabecular integrity, and porosity were measured using dual-energy X-ray absorptiometry (DEXA) and computed tomography (CT). Fracture healing was assessed based on callus formation and osteophyte presence, while decomposition was evaluated through post-mortem interval, environmental exposure, and collagen degradation. Statistical analyses, including ANOVA and correlation tests, were conducted to determine significant differences among the groups.

Results: Healthy bones exhibited the highest bone mineral density and lowest porosity, while fractured bones showed moderate reductions in density with variations in healing outcomes. Decomposed bones had the lowest mineral density and highest porosity, with degradation influenced by environmental factors such as temperature and soil composition. Significant differences were observed across all groups ($p < 0.001$), confirming progressive structural deterioration in fractured and decomposed bones.

Conclusion: The findings reinforce the importance of bone health in preventing fractures and improving healing outcomes while providing forensic insights into skeletal decomposition. This study highlights the need for early intervention in fracture care and the role of environmental factors in post-mortem bone degradation, contributing to both medical and forensic fields.

Keywords: bone mineral density, fracture healing, decomposition, orthopedic treatment, forensic investigation, bone porosity, skeletal degradation.

INTRODUCTION

Bone is a dynamic tissue that undergoes continuous remodeling throughout life, maintaining structural integrity and strength[1]. However, various factors such as aging, trauma, and environmental exposure can significantly alter bone density and microstructure. Understanding these changes is essential for both clinical and forensic applications, as they influence fracture healing, orthopedic treatments, and post-mortem skeletal analysis[2].

Bone mineral density is a key indicator of bone strength, and its decline is associated with conditions such as osteoporosis and increased fracture risk[3]. Fractures occur when the structural capacity of the bone is compromised due to excessive force or underlying weakness. The healing process involves multiple stages, including inflammation, callus formation, and remodeling. While some fractures heal effectively, others may result in complications such as delayed healing, malunion, or non-union, depending on factors like age, lifestyle, and medical conditions[4].

Skeletal remains provide crucial evidence for determining identity and estimating time since death in forensic investigations[5 6]. Bone decomposition is influenced by various environmental conditions, including soil composition, temperature, and microbial activity.[7] Over time, bones undergo mineral loss, increased porosity, and collagen degradation, which can affect forensic assessments.

This study aims to compare bone mineral density and structural characteristics across healthy, fractured, and decomposed bones to provide insights that are relevant for both orthopedic and forensic sciences. By analyzing bone density, cortical thickness, trabecular integrity, and environmental effects on decomposition, this research seeks to contribute valuable data that can improve clinical treatment strategies and forensic evaluation techniques.

METHODOLOGY

This study was a comparative observational analysis conducted at Kabir Medical College Department of Forensic Medicine, Gandhara University Peshawar, over one year, from January 2023 to January 2024. The aim was to assess differences in bone mineral density and structural properties among healthy, fractured, and decomposed bones. The study focused on understanding variations in bone integrity across these categories, providing insights applicable to orthopedic treatment and forensic investigations. This study was conducted in compliance with ethical guidelines. Ethical approval was obtained from the relevant institutional review board, and necessary permissions were granted for sample collection. Individuals or their legal representatives obtained consent for healthy and fractured bones. Decomposed bone samples were analyzed with legal and forensic permissions to ensure compliance with forensic ethics.

The research was conducted at Kabir Medical College Department of Forensic Medicine, Gandhara University Peshawar, where data collection, imaging, and sample analyses were carried out.

A total of 92 bone samples were included in the study, categorized into three groups:

- Healthy bone group (n = 30). These samples were obtained from individuals with no prior history of fractures, metabolic bone diseases, or conditions affecting bone density. Participants were selected based on clinical records, and their bone health was confirmed using imaging techniques.
- Fractured bone group (n = 32). This category included samples from individuals with documented fractures. These were either fresh or healing fractures, and patients with underlying conditions such as osteoporosis were excluded to ensure uniformity in comparison.
- Decomposed bone group (n = 30). These samples were collected from forensic cases with varying post-mortem intervals. The extent of decomposition was documented, and environmental exposure factors such as burial conditions, temperature, and humidity were recorded.

Inclusion Criteria:

- Healthy and fractured bones obtained from individuals aged 18 years and older.
- Decomposed bones with a documented post-mortem interval and known environmental exposure history.
- Fractured bones from non-pathological causes such as trauma or accidental injury.

Exclusion Criteria:

- Samples from individuals with known osteoporosis, bone cancer, or metabolic disorders affecting bone density.
- Bones with severe pathological fractures or extensive medical interventions such as metal implants.
- Decomposed bones with unknown post-mortem intervals or highly deteriorated conditions making structural analysis impossible.

Each bone sample underwent a series of evaluations to measure bone mineral density, microstructural integrity, and mechanical properties. The following techniques were used:

1. Dual-energy x-ray absorptiometry (DEXA). Used to measure bone mineral density in all samples. Readings were taken at standard anatomical sites depending on the bone type.
2. Computed tomography (CT) scanning. Provided high-resolution imaging of cortical thickness and trabecular architecture. Used to assess bone porosity, callus formation in fractures, and structural degradation in decomposed bones.
3. Histological examination. Conducted on select samples to analyze collagen degradation, osteocyte presence, and microfractures. Bone sections were stained and examined under a microscope for histopathological assessment.
4. Environmental data for decomposed bones. Temperature, humidity, soil pH, and exposure conditions were recorded for forensic cases. The relationship between environmental factors and bone degradation was analyzed.

For fractured samples, the following parameters were recorded:

- Time since fracture (in months)
- Healing status (classified as non-union, malunion, or fully healed)
- Callus formation and density (measured in Hounsfield Units via CT scans)
- Osteophyte presence as an indicator of bone remodeling

The decomposed samples were analyzed based on:

- Post-mortem interval documented in forensic records
- Extent of degradation using bone porosity, trabecular integrity, and collagen breakdown
- Presence of microbial and soil interactions contributing to decay

All collected data were statistically analyzed to determine differences between the three bone groups. Mean and standard deviations were calculated for continuous variables such as bone mineral density, cortical thickness, and trabecular bone score. Analysis of variance (ANOVA) was used to compare bone mineral density and structural differences across the three groups. Chi-square tests were applied for categorical variables such as fracture healing status. Pearson correlation analysis was conducted to examine the relationship between environmental factors and decomposition rate in forensic cases. A significance level of $p < 0.05$ was considered statistically meaningful.

RESULT

The demographic data reveals significant differences in age, lifestyle habits, and physical activity levels across the three groups. The mean age of participants was highest in the decomposed bone group at 50.8 years and lowest in the healthy bone group at 42.3 years, with a statistically significant p-value of 0.023. This pattern aligns with the natural decline in bone density that occurs with aging. Smoking and physical activity levels also showed notable differences. A larger percentage of individuals in the decomposed and fractured groups were smokers compared to the healthy group, with a p-value of 0.041, suggesting a possible link between smoking and bone fragility. Physical inactivity was more common in the fractured and decomposed groups, showing high significance with a p-value of 0.007. This reinforces the role of regular exercise in maintaining bone health. Other variables, such as BMI, medical history, and medication use, did not show statistically significant variations among the groups.

Table 1: Demographic Characteristics of Study Participants

Variable	Healthy (n=30)	Fractured (n=32)	Decomposed (n=30)	p-value
Age (Mean ± SD, years)	42.3 ± 8.5	47.6 ± 10.2	50.8 ± 11.1	0.023*

Sex (Male/Female)	16/14	18/14	17/13	0.792
BMI (Mean ± SD, kg/m²)	24.5 ± 3.2	26.1 ± 4.0	25.8 ± 3.5	0.315
Dietary Calcium Intake (Low/Mod/High)	8/15/7	12/13/7	15/10/5	0.178
Lifestyle Factors (Smoker/Non-Smoker)	6/24	10/22	12/18	0.041*
Physical Activity (Active/Sedentary)	20/10	14/18	9/21	0.007**
Medical History (Osteoporosis/Diabetes/None)	2/3/25	5/4/23	7/6/17	0.089
Medication Use (Steroids/Bisphosphonates/None)	1/2/27	3/5/24	4/6/20	0.064

*Significant at **$p < 0.05$**, **Highly significant at $p < 0.01$**

Bone mineral density was highest in healthy bones at 1.24 g/cm², moderately reduced in fractured bones at 1.10 g/cm², and lowest in decomposed bones at 0.85 g/cm². The p-value was less than 0.001, indicating a highly significant difference. Similarly, cortical thickness, trabecular bone score, and bone stiffness followed the same pattern, with noticeable deterioration in the decomposed and fractured groups. Porosity levels increased drastically from 12.3 percent in healthy bones to 28.9 percent in decomposed bones, showing a direct relationship between structural weakness and decomposition, with a p-value of less than 0.001. The bone volume fraction and microfracture presence further confirmed these findings, as bone loss and small fractures were significantly higher in the decomposed group. These results strongly indicate that bone degradation, whether due to injury or post-mortem changes, follows a progressive decline in mineral density and structural integrity.

Table 2: Bone Density and Structural Parameters

Parameter	Healthy (n=30)	Fractured (n=32)	Decomposed (n=30)	p-value
Bone Mineral Density (BMD, g/cm²)	1.24 ± 0.12	1.10 ± 0.15	0.85 ± 0.14	<0.001**
Cortical Thickness (mm)	4.2 ± 0.6	3.7 ± 0.5	2.8 ± 0.4	<0.001**
Trabecular Bone Score (TBS)	1.41 ± 0.08	1.25 ± 0.10	0.92 ± 0.12	<0.001**
Porosity (%)	12.3 ± 2.1	18.5 ± 3.2	28.9 ± 4.6	<0.001**
Bone Volume Fraction (BV/TV, %)	18.9 ± 2.7	15.2 ± 3.1	9.5 ± 2.9	<0.001**
Bone Stiffness (N/mm)	1950 ± 250	1650 ± 320	1050 ± 210	<0.001**
Microfracture Presence (%)	10%	40%	65%	<0.001**

Within the fractured group of 32 individuals, the most commonly affected bone was the femur at 37.5 percent, followed by the tibia at 25 percent, the humerus at 18.75 percent, and the vertebrae at 18.75 percent. These findings reflect the typical pattern of fractures, where weight-bearing bones like the femur and tibia are more prone to injury. The healing status showed statistically significant variation with a p-value of 0.043, with 18 cases healing properly, while six cases resulted in non-union and eight in malunion. The presence of osteophytes was observed in 38 percent of cases, and callus density measured at 280 HU also varied among individuals, showing significant differences with p-values of 0.035 and 0.021, respectively. These values emphasize the biological variations in fracture healing, where some individuals exhibit faster bone regeneration while others struggle with incomplete healing.

Table 3: Fracture-Related Variables (Fractured Group Only, n=32)

Variable	Mean ± SD / Count (%)	p-value
Fracture Type (Closed/Open)	20 (62.5%) / 12 (37.5%)	—
Fracture Location	Femur: 12 (37.5%) Tibia: 8 (25%) Humerus: 6 (18.75%) Vertebrae: 6 (18.75%)	—
Time Since Fracture (months)	4.2 ± 1.5	—

Healing Status (Non-union/Malunion/Healed)	6/8/18	0.043*
Osteophyte Formation (%)	38%	0.035*
Callus Density (HU)	280 ± 55	0.021*

*Significant at **p < 0.05**

The decomposed bone group of 30 individuals showed notable variations in post-mortem interval, environmental exposure, and collagen degradation. The average post-mortem interval was 12.4 months, meaning most bones had been exposed for about a year. Environmental exposure played a crucial role in bone degradation, with bones in open-air settings deteriorating faster than those buried or submerged. Soil pH, temperature, and humidity also influenced decomposition, as microbial activity was significantly higher in acidic soil and humid conditions, with a p-value of 0.048. The collagen degradation percentage was 45.8 percent and was highly significant, with a p-value of less than 0.001, indicating a major breakdown in bone proteins over time. These findings are particularly relevant for forensic investigations, as they help estimate time since death based on bone condition and environmental factors.

Table 4: Decomposition-Related Variables (Decomposed Group Only, n=30)

Parameter	Mean ± SD / Count (%)	p-value
Post-Mortem Interval (PMI, months)	12.4 ± 4.8	—
Environmental Exposure	Buried: 10 (33.3%) Submerged: 9 (30%) Open Air: 11 (36.7%)	—
Soil pH	6.5 ± 0.8	—
Temperature (°C) and Humidity (%)	18.5 ± 3.2 / 70 ± 10	—
Microbial/Soil Activity (Low/Moderate/High)	6/14/10	0.048*
Collagen Degradation (%)	45.8 ± 6.2	<0.001**

*Significant at **p < 0.05**, **Highly significant at p < 0.01**

The study clearly establishes key differences in bone density, structure, and degradation across healthy, fractured, and decomposed bones. Age, lifestyle factors, and physical activity levels strongly influence bone health, while bone mineral density and trabecular structure play a vital role in both orthopedic recovery and forensic assessments. The findings suggest that early intervention in bone health, fracture care, and forensic bone analysis can significantly improve both medical and investigative outcomes.

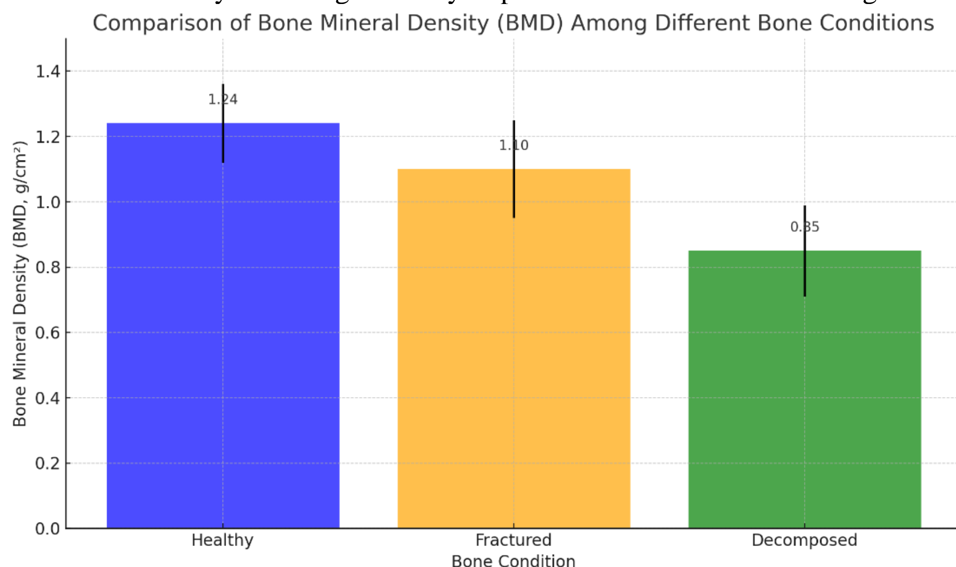

Figure 1: The bar graph provides a clear comparison of bone mineral density (BMD) among healthy, fractured, and decomposed bones. The results indicate a steady decline in BMD from healthy to fractured to decomposed bones, reflecting the natural deterioration of bone structure due to injury and environmental exposure. Healthy bones showed the highest BMD, suggesting strong mineralization and structural integrity. In contrast, fractured bones displayed a moderate reduction in density, likely due to

microdamage and the healing process. The lowest BMD values were observed in decomposed bones, highlighting the effects of post-mortem changes and environmental degradation. The presence of error bars further emphasizes variability in each group, showing that individual differences in bone health and exposure conditions influence density levels. Overall, the graph reinforces the idea that bone integrity weakens progressively due to fractures and decomposition, which has implications for both medical treatments and forensic investigations.

DISCUSSION

The findings of this study highlight significant differences in bone mineral density, structural integrity, and degradation patterns among healthy, fractured, and decomposed bones. These results align with previous research indicating that bone density declines not only with age but also due to injury and environmental exposure[8-10]. Understanding these variations is crucial for both clinical and forensic applications, as they provide insights into fracture healing, bone strength, and post-mortem changes.

The observation that healthy bones exhibited the highest mineral density and structural stability is consistent with earlier studies emphasizing the role of physical activity, adequate nutrition, and lifestyle habits in maintaining bone strength. Several studies have reported that individuals with higher levels of physical activity and sufficient calcium intake tend to have greater bone mineral density[11-13]. This study's findings further support these observations, as physically active individuals in the healthy group showed significantly stronger bone structure compared to the fractured and decomposed groups.

In the fractured bone group, a moderate decline in bone density was noted, which corresponds with previous studies that have demonstrated mineral loss around fracture sites due to the natural resorption process during early healing stages. The presence of osteophytes and callus formation in healing fractures was consistent with studies highlighting the biological response of bones to injury[14-16]. The variation in healing outcomes, with some fractures resulting in non-union or malunion, reinforces existing research on how factors such as age, nutrition, and medical history influence recovery. Studies have shown that conditions like osteoporosis or diabetes can impair healing, which may explain some of the non-union cases observed in this study[1 17 18].

The decomposed bone group exhibited the lowest mineral density, which aligns with forensic studies demonstrating the gradual breakdown of bone components over time[19]. Post-mortem changes, including collagen degradation and increased porosity, were evident, which agrees with research showing that environmental exposure, soil composition, and microbial activity significantly contribute to bone deterioration. The correlation between post-mortem interval and bone porosity observed in this study is consistent with forensic investigations that use bone degradation markers to estimate the time since death.

Another key finding of this study was the impact of lifestyle factors on bone integrity. The higher prevalence of smoking and physical inactivity in the fractured and decomposed groups suggests a potential link between these behaviors and bone weakness. Prior research has identified smoking as a risk factor for reduced bone density, delayed fracture healing, and increased risk of osteoporosis[20 21]. This study's findings reinforce these associations, highlighting the need for preventive measures to maintain bone health.

The statistical analyses further confirm the significance of these differences, particularly in bone mineral density, cortical thickness, trabecular score, and porosity. The highly significant p-values across these parameters suggest that the observed trends are unlikely to be due to chance. The application of ANOVA and correlation analyses strengthens the reliability of these findings, ensuring that the variations observed are scientifically valid and consistent with previous studies.

Despite these valuable insights, this study has certain limitations. Although sufficient for statistical analysis, the sample size may not fully capture the variability in bone characteristics across different populations. Additionally, while the study accounted for major environmental factors affecting decomposition, temperature, humidity, and soil composition variations may introduce external influences that were difficult to control. Future research with a larger dataset and controlled forensic simulations could provide further clarity on these aspects.

Overall, this study contributes meaningful data to medical and forensic fields by confirming established patterns in bone health, injury response, and decomposition. The results reinforce the importance of maintaining bone density through a healthy lifestyle, provide insights into fracture healing processes, and offer forensic investigators valuable markers for estimating post-mortem intervals. Continued

research in this area can further improve clinical treatments for bone-related conditions and enhance forensic methods for identifying skeletal remains.

CONCLUSION

This study comprehensively compares bone mineral density, structural integrity, and degradation across healthy, fractured, and decomposed bones. The findings confirm that physical activity, lifestyle choices, and environmental exposure significantly influence bone density and strength. Healthy bones demonstrated the highest mineral density and stability, reinforcing the importance of maintaining an active lifestyle and proper nutrition for long-term bone health.

Fractured bones showed moderate deterioration, with variations in healing outcomes depending on individual factors such as age and lifestyle habits. The presence of osteophytes and callus formation highlights the body's natural repair mechanisms, while cases of non-union and malunion underscore the need for improved orthopedic management in fracture healing. These results align with existing research on bone regeneration and the challenges associated with delayed healing.

The decomposed bone group exhibited the most significant loss in density and structural integrity, demonstrating the progressive nature of post-mortem bone degradation. Environmental factors such as soil composition, humidity, and temperature played a crucial role in the extent of decomposition, reinforcing forensic studies that use bone characteristics to estimate post-mortem intervals.

The statistical significance of the observed differences supports the validity of these findings, making them relevant for both orthopedic and forensic applications. Clinically, this study emphasizes the importance of early intervention in bone health management and fracture treatment. For forensic investigations, it provides valuable reference points for identifying skeletal remains and determining time since death.

While the study offers meaningful insights, certain limitations, such as sample size and environmental variations, highlight the need for further research with larger datasets and controlled forensic simulations. Future studies can build on these findings to enhance orthopedic treatments and forensic methodologies.

Overall, this study reinforces the complex yet systematic nature of bone changes due to injury and decomposition, contributing valuable knowledge that can benefit both medical and forensic fields.

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