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Intelligent Approaches to Morphofunctional Assessment of Bone Tissue

Rakhmatova M. R.

PhD, Associate Professor, Department of Clinical Pharmacology, Bukhara State Medical Institute, Bukhara, Uzbekistan

Abstract **Background:** Early detection of decreased bone mineral density (BMD) and identification of risk factors are essential for timely prevention and intervention. Recent advances in artificial intelligence (AI) and digital health technologies offer new opportunities for non-invasive and personalized assessment of bone health. **Methods:** This study is dedicated to the development and clinical evaluation of the BoneTrack mobile application based on artificial intelligence, designed for the integrated assessment of bone metabolism and bone mineral density parameters. The system utilizes anthropometric data, dietary patterns, physical activity levels, and lifestyle factors. An individual risk profile is generated using the Bone Tissue Density Index (BTDI), enabling classification into high-, moderate-, and low-risk groups. Key determinants such as Body Mass Index (BMI), calcium and vitamin D intake, and physical activity are analyzed in a comprehensive framework. **Results:** The results demonstrated that the BoneTrack system is an effective digital tool for early detection of reduced bone mineral density and prediction of osteoporosis risk. The application showed improved speed, accuracy, and personalization compared to conventional diagnostic approaches. It also enabled identification of subclinical changes in BMD and facilitated risk stratification across the study population. **Conclusion:** The BoneTrack application represents a promising AI-driven solution for morphofunctional assessment of bone tissue. Its integration of multiple risk factors and predictive modeling supports early diagnosis and the development of individualized preventive strategies, potentially improving clinical outcomes and reducing the burden of osteoporosis.

Keywords Bone metabolism, Body Mass Index, Artificial intelligence, BoneTrack, BTDI, Digital medicine, Mobile application, Anthropometry

1. Introduction

At present, diseases of the skeletal system, particularly osteoporosis, osteopenia, and metabolic bone disorders, are increasing globally, posing significant diagnostic and preventive challenges for modern medicine. According to the World Health Organization (WHO), the incidence of osteoporosis-related fractures continues to rise significantly in the context of population aging, contributing to increased disability and mortality (WHO, 2023). A number of researchers emphasize that the early detection of morphofunctional changes in bone tissue represents a critical stage in disease prevention (Kanis et al., 2019; Cosman et al., 2014) [1,4,5,9,10]. These pathological conditions are often characterized by a prolonged subclinical course and late diagnosis, which substantially increases the risk of complications, including fractures and disability. Therefore, early-stage detection and assessment of the morphofunctional state of bone tissue remain urgent scientific and practical challenges [2,3,6,7,9].

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Conventional diagnostic methods, including radiography and densitometry, play an important role in assessing bone mineral density; however, they do not always enable the detection of early metabolic changes in bone tissue. Moreover, these approaches often fail to comprehensively account for individual anthropometric characteristics, lifestyle factors, and metabolic features. As a result, limitations arise in identifying risk groups and developing personalized preventive strategies [12,14,15,19].

The rapid advancement of digital medicine and artificial intelligence technologies offers innovative solutions to these challenges. In particular, AI-based algorithms enable the processing of large volumes of clinical, morphological, and anthropometric data, thereby facilitating a comprehensive and integrated assessment of bone tissue status. This approach allows not only for early disease detection but also for risk prediction and the development of individualized preventive interventions.

From this perspective, the development of platforms based on mobile applications and intelligent digital systems for the assessment of bone tissue status is of particular scientific interest. Such systems enable real-time monitoring, analysis of individual user parameters, and the provision of personalized

recommendations. Furthermore, their implementation in clinical practice contributes to improved diagnostic accuracy, more efficient use of healthcare resources, and optimization of preventive measures [13,16,17,18].

Thus, the integration, modeling, and analysis of intelligent digital systems for assessing the morphofunctional state of bone tissue represent not only a theoretical concern but also a problem of considerable practical importance, and are regarded as one of the priority directions of modern medicine.

The **aim** of this study is to develop an artificial intelligence –based BoneTrack mobile system for the assessment of bone metabolism, incorporating anthropometric parameters, dietary patterns, physical activity, and lifestyle factors, and to evaluate its clinical effectiveness. Additionally, the study seeks to enable early detection of osteoporosis risk using the Bone Tissue Density Index (BTDI) and to substantiate individualized preventive strategies.

2. Materials and Methods

This study is aimed at the development of the BoneTrack mobile digital system based on artificial intelligence and the scientific evaluation of its clinical effectiveness. The system is designed for a comprehensive assessment of bone metabolism through the integrated analysis of anthropometric parameters, dietary characteristics, physical activity levels, and lifestyle factors.

The methodological framework includes the evaluation of the morphofunctional state of bone tissue using a digital modeling approach, the processing of heterogeneous clinical and individual data streams through machine learning algorithms, and the analysis of results using an integrated predictive modeling framework. Particular emphasis is placed on the early detection of osteoporosis risk using the Bone Tissue Density Index (BTDI), as well as on risk stratification and the development of individualized preventive strategies.

In addition, the study involves the clinical assessment of the diagnostic accuracy, sensitivity, and practical applicability of the developed system, along with a comparative analysis against conventional diagnostic methods to substantiate its relevance in digital medicine.

Within the framework of this study, the BoneTrack mobile application, based on artificial intelligence, was developed and subjected to experimental and practical validation for the integrated assessment of bone metabolism and early detection of osteoporosis risk. The application collects baseline anthropometric data—including height, body weight, and age—according to a standardized protocol. Furthermore, data on dietary habits, daily physical activity, environmental and external factors influencing bone metabolism, as well as general lifestyle characteristics, are collected a structured questionnaire.

The collected data undergo an initial normalization process, followed by the calculation of Body Mass Index (BMI). Subsequently, these indicators are incorporated into a multivariate statistical and analytical framework for integrated assessment. To evaluate the functional state of bone tissue, a machine learning–based artificial intelligence model was employed. This model enables the identification of complex correlations, latent interactions, and non-linear relationships among input variables.

As an output, the Bone Tissue Density Index (BTDI) is automatically calculated and used as an integrated digital indicator reflecting the structural and functional state of bone tissue.

The study utilized digital health technologies, large-scale data processing techniques, and advanced statistical analysis methods, including descriptive statistics, correlation analysis, regression modeling, and classification algorithms such as decision trees, random forest, and other machine learning approaches.

Based on the obtained results, participants were stratified into three primary clinical risk groups according to bone metabolism status: high risk, moderate risk, and low risk (normal).

Furthermore, the diagnostic performance of the developed system—including sensitivity, specificity, and overall classification accuracy—was evaluated through comparative analysis with conventional clinical assessment methods. The findings provide a scientific basis for the application of the system in real clinical settings and demonstrate its potential in the field of digital medicine.

3. Results and Discussion

The BoneTrack mobile digital application developed in this study enabled a multifactorial (multiparametric) assessment of bone metabolism through the integrated analysis of anthropometric, functional, and lifestyle-related factors. The system's clinical and analytical functionality was expressed through the Bone Tissue Density Index (BTDI), based on which users were stratified into three principal risk categories: high, moderate, and low (normal) risk groups.

Statistical analysis and processing of the collected data using machine learning algorithms revealed significant and reliable correlations between bone metabolism status and anthropometric as well as lifestyle-related factors. In particular, individuals with a Body Mass Index (BMI) ≥ 25 kg/m² demonstrated a tendency toward decreased bone mineral density, accompanied by significantly reduced BTDI values. In this group, hypodynamia, high-calorie yet nutritionally imbalanced diets (characterized by deficiencies in calcium, vitamin D, and protein) were identified as key pathogenic risk factors.

Participants classified within the high-risk group exhibited pronounced disturbances in the structural and functional stability of bone tissue, indicating a high probability of osteoporosis development. This group was characterized by complex pathophysiological alterations, including reduced bone remodeling activity, decreased mineralization dynamics, and an overall decline in metabolic activity.

In the moderate-risk group, anthropometric indicators were generally within physiological ranges; however, partial imbalances in lifestyle factors were observed. Irregular physical activity, sedentary behavior, and insufficient intake of macro- and micronutrients were identified as contributing factors to subclinical instability in bone metabolism. These conditions may increase the risk of future degenerative changes in bone tissue.

In contrast, individuals in the low-risk (normal) group exhibited BMI values within physiological norms, along with regular physical activity, balanced nutrition, and healthy lifestyle patterns, all of which contributed to stable bone metabolism. BTDI values in this group remained within normal ranges, reflecting physiologically maintained processes of mineralization and bone remodeling.

The discussion highlights that bone metabolism represents a complex multifactorial biological system closely associated with anthropometric, nutritional, and behavioral determinants. These factors act as key regulatory mechanisms influencing the morphofunctional state of bone tissue. Therefore, integrated digital assessment systems that simultaneously account for these variables demonstrate high scientific and practical value in clinical diagnostics and preventive medicine.

The AI-based BoneTrack system demonstrated several advantages over conventional diagnostic methods. Specifically, it enables real-time processing of large datasets, generation of individualized risk profiles, dynamic monitoring, and predictive modeling. These capabilities support its application not only as a screening tool but also as a comprehensive platform for digital preventive medicine.

Moreover, the implementation of automated clinical decision support mechanisms contributes to reducing diagnostic errors, minimizing subjective bias, and improving overall diagnostic accuracy. The results confirm that the BoneTrack system outperforms traditional methods in terms of speed, accuracy, and degree of personalization.

Overall, the findings indicate that digital medicine and artificial intelligence technologies represent highly effective tools for the early detection of bone metabolism disorders, accurate risk stratification, and the development of personalized preventive strategies. In this context, the BoneTrack system can be considered a promising solution for integration into clinical practice and a significant component of the ongoing digital transformation in healthcare.

4. Conclusions

The results of this study provide a scientific rationale for the necessity of an integrated approach to assessing bone metabolism, incorporating anthropometric parameters, dietary characteristics, physical activity levels, and lifestyle factors. The findings demonstrate that the morphofunctional state of bone tissue is determined not by a single clinical parameter, but by a complex system of multifactorial biological and behavioral determinants.

The developed BoneTrack mobile digital application, based on artificial intelligence algorithms, enabled the calculation of the Bone Tissue Density Index (BTDI) and the stratification of users according to their osteoporosis risk levels. The system proved to be an effective digital tool for the early detection of osteoporosis risk and for the predictive assessment of subclinical changes in bone tissue.

The study findings indicate that, in the high-risk group, hypodynamia, excess body weight, and dietary mineral deficiencies are the primary contributing factors to impaired bone metabolism. In the moderate-risk group, latent functional alterations were identified, whereas in the low-risk group, a healthy lifestyle was associated with stable bone metabolism.

Furthermore, the BoneTrack system demonstrated several advantages over conventional diagnostic methods. These include real-time data processing, the generation of individualized risk profiles, dynamic monitoring, and automated decision -making capabilities. Such features contribute to improved diagnostic accuracy and reduction of subjective bias in clinical practice.

Overall, the findings confirm that artificial intelligence and digital health technologies represent highly effective tools for the early detection of bone metabolism disorders, accurate risk stratification, and the development of personalized preventive strategies. In this context, the BoneTrack system can be considered a promising and innovative platform with strong potential for wide implementation in clinical diagnostics and digital healthcare systems.

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