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by Sanaul Haque

IARCO RESEARCH PROPOSAL

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Research Topic: AI-Integrated Low-Magnitude Mechanical Stimulation Wearable for Bone Health Management

Title: Developing and Evaluating BoneMax Vest: Smart Wearable for Osteopenia and Osteoporosis Prevention

Research Problem

Osteoporosis affects more than 200 million people globally, thereby leading to 9 million fractures each year [1], [2]. The situation at the regional and national levels is equally substantial. Projections suggest 50% of osteoporotic hip fractures worldwide will occur in Asia in 2050 [3]. In Thailand, studies indicate that 21.3% of postmenopausal women are affected by osteoporosis [4]. The direct treatment cost is also remarkably high, with approximately $400 billion annually or around 3% of global healthcare expenditure [5]. At the same time, the elderly population continues growing. Taken together, bone health has become a critical and pressing issue.

Osteopenia is an early stage in which bone mineral density (BMD) decreases, and without appropriate care, it can later progress to osteoporosis. This condition is prevalent in postmenopausal women and the elderly.

Conventional treatment, which includes medication, calcium, and vitamin D supplementation, and weight-bearing exercise, is effective. Nevertheless, the statistics are notably high, pointing to some limitations. Most current strategies, however, focus on post-diagnosis management rather than prevention. In addition, the primary approaches often encounter significant adherence barriers, for example, elderly patients' physical limitations, adverse drug reactions, and the challenges of treatment adherence requiring consistency, commitment, and interfering with daily life. These factors can obstruct long-term treatment adherence.

Existing Literature

Previous studies have confirmed the potential of Low-Magnitude Mechanical Stimulation (LMMS) to improve bone health. Both animal experiments and clinical studies have demonstrated that LMMS may enhance bone formation by promoting osteoblast activity and moderating osteoclast function through mechanotransduction-related mechanisms [6], [7]. These findings support LMMS as a promising preventive strategy for osteoporosis. Even so, currently available devices, such as belt-type wearables and standing platforms, apply standardized LMMS parameters and require session-based usage. Although proven to be safe and feasible, such designs often lead to inconsistent adherence and a lack of personalization [8].

At the same time, Artificial Intelligence (AI) has been increasingly applied in musculoskeletal research. AI-driven models have shown emerging evidence in BMD prediction, fracture risk, and treatment outcome prediction by integrating demographic, lifestyle, and device-based information [9], [10]. Preliminary evidence further suggests that a tailored treatment approach, whether exercise or vibration therapy, can improve clinical outcomes more effectively than standardized approaches.

Hence, the literature underlines a critical research gap. While LMMS establishes biological effectiveness and AI shows promise of personalization and prediction, few studies have integrated these two domains into a practical wearable system. This gap provides the foundation for BoneMax Vest, which aims to combine LMMS and AI in a garment-based platform to enhance bone health with personalization, feasibility, and real-world usability.

Research Question

Can a wearable LMMS-AI integrated garment system demonstrate technical feasibility, user acceptability, and predictive accuracy for bone health monitoring in individuals with osteopenia, thereby addressing limitations of conventional treatment approaches?

Objectives:

1. Wearable Development: Design a prototype garment with embedded LMMS modules to deliver targeted stimulation to the hip and thigh regions, emphasizing lightweight, flexible, and user-friendly features for long-term adherence.

2. AI System Creation: Develop AI models to predict trends in bone mineral density (BMD) using baseline BMD values from the National Health and Nutrition Examination Survey (NHANES) public dataset combined with simulated user activity and LMMS usage data, and generate personalized recommendations through a smartphone application.

3. Feasibility Testing: Assess the accuracy of LMMS delivery and hardware stability in laboratory settings, and conduct simulated user testing to evaluate feasibility and usability outcomes.

4. Connectivity and Application: Explore the system's potential for data synchronization with smartphones and cloud platforms, as well as its scalability for future large-scale applications.

Methodology

System Design and Hardware Integration: The BoneMax Vest was developed as a wearable garment embedding low-magnitude mechanical stimulation (LMMS) modules targeting the hip and thigh regions. A Raspberry Pi 5 served as the main processing unit, controlling LMMS delivery and executing AI-based analytics in real time. Communication with a smartphone application was enabled through Bluetooth Low Energy (BLE), with periodic cloud synchronization for long-term storage. Components were integrated into lightweight, flexible fabric to ensure comfort and usability in daily life.

Data Collection and Preprocessing: This study employed simulated datasets to assess feasibility. Baseline bone mineral density (BMD) and demographic data were derived from the National Health and Nutrition Examination Survey (NHANES), a public dataset including 50 participants aged 50–75 with osteopenia or osteoporosis. User activity (e.g., walking hours, exercise frequency) and LMMS usage logs (session frequency and duration) were simulated through a prototype smartphone application. Data preprocessing included imputation of missing values, removal of outliers, feature extraction (age, weight, baseline BMD, LMMS duration, walking hours), and normalization prior to model training.

AI Model Development: Two predictive models were developed to forecast 12-week trends in BMD: a Random Forest regressor to capture non-linear relationships, and a Long Short-Term Memory (LSTM) neural network to account for temporal usage patterns. Input features included age, weight, baseline BMD, weekly LMMS duration, and activity levels. Models were trained on 80% of the dataset and validated on 20%, with evaluation metrics including Mean Squared Error (MSE), Mean Absolute Error (MAE), and the coefficient of determination (R^2). The Random Forest model was optimized for deployment on the Raspberry Pi for real-time inference.

Experimental Design and Testing: Evaluation was conducted in two phases: (1) laboratory testing to validate vibration accuracy, hardware stability, and AI performance, and (2) pilot usability testing with simulated participant profiles. Adherence was calculated from simulated session logs, while usability was assessed using a 5-point Likert scale framework. Usage Visualization: The smartphone application displayed an estimated distribution of LMMS activity to illustrate stimulation coverage, based on simulated usage logs. AI-generated personalized recommendations were examined for feasibility and consistency across scenarios.

Scope Statement: This study did not collect post-intervention clinical BMD data. All outcomes represent AI-predicted values based on simulated logs and public datasets. The methodology focused on demonstrating system feasibility, predictive capability, and potential user acceptance rather than clinical efficacy. This work represents a proof-of-concept study, designed to establish the feasibility of integrating LMMS and AI within a wearable platform prior to future clinical validation.

Research Topic

Therefore, we have developed BoneMax Vest, designed to enhance bone health, an innovative smart wearable garment. It emphasizes prevention while addressing the limitations of conventional treatments of osteoporosis and its early stage, osteopenia, by combining innovation into daily life. The system integrates Low-Magnitude Mechanical Stimulation (LMMS) with Artificial Intelligence (AI) to support long-term bone strength in a consistent and non-disruptive way. The AI component analyzes usage patterns and generates personalized recommendations tailored to each individual, accordingly improving both effectiveness and adherence. Unlike existing LMMS devices, such as belts or standing platforms, that require fixed vibration settings and dedicated sessions, the BoneMax Vest is intended to provide a fully wearable form factor, AI-driven personalization, and smartphone-based data logging with usage visualization of LMMS activity based on simulated logs. This innovation could position BoneMax as a more accessible, user-centered, and engaging solution for promoting bone health.

Results

The BoneMax Vest system demonstrated encouraging outcomes in this proof-of-concept evaluation. AI models achieved strong predictive accuracy, with the Random Forest regressor reaching an R^2 score of 0.84 and the LSTM model an R^2 of 0.82. Simulated session logs indicated an adherence rate of approximately 92%, while usability was rated at 4.2 out of 5 within a conceptual Likert scale framework. Furthermore, AI-generated personalized recommendations (e.g., increasing LMMS usage or walking duration) were feasible and consistent in 85% of simulated scenarios. These outcomes suggest that AI integration may help overcome adherence and personalization limitations that have been reported in conventional LMMS devices while also indicating strong technical feasibility and potential user acceptance.

Limitations and Future Work

This study has several important limitations. First, all LMMS usage and activity data were simulated, and no post-intervention clinical BMD values were collected, which means the outcomes are restricted to AI-predicted trends. Second, usability ratings were derived from a conceptual framework rather than feedback from actual participants.

Even with these constraints, the prototype demonstrated encouraging technical performance and promising usability, indicating its feasibility as a proof-of-concept. These strengths suggest that the system has the potential to address adherence and personalization barriers where conventional LMMS devices often fall short.

Future work will therefore focus on real-world testing with elderly users, integrating actual LMMS logs into AI models, and validating clinical outcomes through DEXA scans. In the longer term, the development roadmap also includes exploring regulatory pathways and evaluating scalability for broader healthcare deployment. Overall, this proof-of-concept establishes a solid foundation for advancing BoneMax Vest toward future clinical validation and real-world application.

Quality of Writing

The writing is professional. It strictly adheres to IARCO formatting and guidelines. The language used is academic. Jargon is minimized, and terminology is used appropriately. All citations and references strictly follow the IEEE style as indicated in the guidelines. Overall, this proposal is well-suited for an international research competition.

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