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AI-Enabled Exoskeletal Robotics for Enhancing Mobility, Bone Regeneration, and Functional Rehabilitation in Osteoporosis: A Literature Review

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Abstract. The care of osteoporosis is being revolutionized by developments in AI-enabled exoskeletal robotics, which can improve mobility and facilitate the recovery from fragility fractures. The literature on current advancements in exoskeletal robotics and their therapeutic implications for patients with osteoporosis with particular attention paid to investigations on bone regeneration, functional rehabilitation, and gait analysis, is reviewed in this study, The review focuses on exoskeletons used for mobility aid and polymer-coated synthetic bone grafts, highlighting these technologies' safety, viability, and efficacy.

Keywords. AI-enabled exoskeletal robotics, Osteoporosis management, Fragility Fractures, Bone regeneration, AI, Gate training

1. Introduction

In older populations, osteoporosis and fragility fractures have a substantial negative influence on quality of life because they frequently result in decreased mobility and longer recovery times. Severe cases of fracture have not always responded well to conventional treatment methods, such as medication and physical rehabilitation. Promising options are provided by new developments in Artificial intelligence (AI enabled exoskeletal robotics, improving patient independence, helping with movement, and encouraging bone healing. The ABLE lower-limb exoskeleton for spinal cord injuries [2] and non-wheeled smart walkers with force sensors [1] are two recent developments that have shown promise in enhancing functional recovery through improved gait patterns and safety metrics.

Exoskeletal systems powered by AI incorporate machine learning algorithms to offer individualized rehabilitation regimens. By monitoring patients' progress using sophisticated sensors and data analytics, these devices can modify support levels according to each patient's needs and unique rate of recovery. Virtual reality-enhanced gait rehabilitation systems [8] and hybrid EEG/EOG-based brain/neural hand exoskeletons [4] are two examples of notable advancements in customized patient care. Exoskeletal robotics can help patients with fractures recover more quickly and have better overall outcomes by enabling focused interventions.

2. Background

Osteoporosis, known as a silent disease, is marked by loss of bone mass and structural degradation in its quality. The condition raises the risk of fracture, especially in older people. This is while many studies have reported that experiencing a fracture significantly increases the likelihood of sustaining a subsequent fracture, often referred to as a "Segond fracture ." Traditional fracture management involves a variety of treatments, including physical therapy and medication, depending on the type of fracture, its severity, and its location; these approaches, however, are not always successful, leading to chronic pain, disability, and increased mortality. New opportunities are presented by the incorporation of AI into exoskeletal robotics, including brain/neural hand exoskeletons [4], smart walkers [1], and hybrid gait rehabilitation systems [8]. Studies on gait characteristics and force sensor data analysis have demonstrated these technologies enabled with machine learning capabilities can provide personalized movement analysis [1, 2, 3].

3. Methods

Search Strategy

A systematic search was performed using the Google Scholar search engine. A combination of different keywords was used to identify the relevant studies i.e., "AI-Enabled Exoskeletal Robotics for Osteoporosis and Fragility Fractures". The inclusion criteria included: (a) articles published between 2000 and 2025, (b) those conducted on AI-enabled exoskeletal Robotics technology and osteoporosis as well as osteoporotic/fragility fractures. **Figure 1** shows the PRISMA flow diagram for the systematic review. A total of 2116 studies were identified following the database search; 476 were selected after removing duplicate and irrelevant results. After removing papers with irrelevant keywords, 64 were found to be relevant to this paper's topic. Among them, 10 articles fulfilled the eligibility criteria.

Google Scholar collates results from across the internet and is free to use. As a result, it has received considerable attention as a method for searching for literature, particularly in searches for grey literature, as required by systematic reviews [11]. Hence, we used it as our search engine.

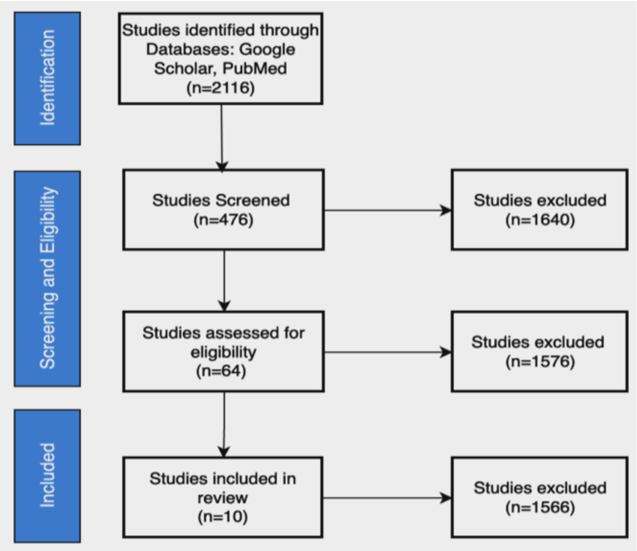

Figure 1: PRISMA flow diagram of the study selection process

4. Results

The included articles pointed out several benefits/applications for AI-enabled exoskeletal robotics in managing patients with fragility fractures:

4.1. Gait Improvement and Mobility Support

Using the ABLE lower-limb exoskeleton and non-wheeled smart walkers, respectively, Ejaz et al. [1] and Wright et al. [2] demonstrated enhanced gait characteristics and balance. They demonstrated notable improvements in step length, gait symmetry, and decreased risk of falling using these technologies.

4.2. Bone Regeneration and Mechanical Support

The efficiency of synthetic and marine-derived porous scaffolds in bone healing was emphasized by Neto and Ferreira [9]. The scaffolds covered with polymers increased mechanical strength and collagen synthesis, promoting bone repair while offering exoskeletal applications.

4.3. Functional Independence and Quality of Life

Soekadar et al. [4] and Spungen et al. [3] discovered that patients who used exoskeletal devices had greater functional independence. While brain/neural hand exoskeletons helped paralyzed veterans regain their independence and fine motor control, they also demonstrated improved mobility.

4.4. Safety, Usability, and User Experience

The significance of user-centered design was highlighted by Costa et al. [8] and Wright et al. [2], whose research revealed favorable user input regarding comfort, safety, and usability. The viability of exoskeletal devices was confirmed through multicenter trials, in which no significant adverse events were recorded.

4.5. Robot-Assisted Arm Training

In a pilot study, MEDICA EM [5] showed that robot-assisted arm training for distal radius fractures improved motor function recovery and shortened recovery duration. The results showed promising results for the potential application of lower-limb exoskeletal devices in conjunction with upper-limb therapy.

4.6. Technological Advancements and Hybrid Integration

Soekadar et al. [4] and Costa et al. [8] investigated hybrid strategies of virtual reality, exoskeletons, and brain-computer interfaces. These devices made improved neuronal feedback and quicker recovery possible.

Despite these encouraging results, Payr et al. [6] and Sulzer et al. [7] pointed up issues with accessibility and cost, as well as the need for standardized clinical evaluation. They suggested more clinical trials and long-term efficacy studies to be conducted to confirm their results.

5. Discussion

AI-enabled exoskeletal robotics improve mobility, balance, and fracture repair outcomes, thereby addressing important difficulties in fracture therapy. Robotic therapies have been shown to significantly enhance gait patterns and safety metrics in several studies such as Wright et al. [2] and Ejaz et al. [1]. Accessibility, cost, and long-term efficacy, however, were still a concern in several patient populations. This suggests the need for more research to develop customized rehabilitation regimens utilizing exoskeletal systems and standardized clinical evaluations.

These technologies are essential for lowering hospitalization rates and preventing subsequent fractures while increasing mobility. Precise movement control is made possible by AI algorithms, which also guarantee ideal pressure distribution and reduce the possibility of difficulties. Synthetic and marine-derived porous scaffolds, as noted by Neto and Ferreira [9], can enhance robotic systems by encouraging bone regeneration while providing mechanical support, resulting in a comprehensive approach to fracture treatment.

6. Conclusions

By integrating technological innovation with clinical rehabilitation practices, AI-enabled exoskeletal robotics have the potential to revolutionize osteoporotic fracture management. Important developments like the ABLE lower-limb exoskeleton [2], smart walkers with force sensors [1], and hybrid brain/neural hand exoskeletons [4] show notable progress in promoting mobility and fracture recovery, facilitating improved gait patterns, bone healing, and increased patient independence, addressing critical needs in osteoporosis care.

Additionally, the literature analysis highlights how crucial safety, usability, and individualized care are for exoskeletal applications. Notwithstanding encouraging outcomes, issues with cost, accessibility, and the requirement for uniformity throughout clinical trials still exist. Future research should concentrate on improving exoskeletal designs and increasing clinical validations to guarantee wider use and long-term advantages for patients with osteoporosis.

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