RESEARCH PAPER

# Predictors of Functional Recovery Following Bone Fractures: A Comparative Secondary Database Study.

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## ABSTRACT

**Background:**
Bone fractures are a major cause of morbidity, disability, and reduced quality of life worldwide. Although advances in surgical techniques and rehabilitation have improved fracture management, functional recovery remains highly variable among patients. Numerous patient-related, fracture-related, treatment-related, and psychosocial factors influence recovery, making early prognostication essential for individualized management and rehabilitation planning. While substantial evidence exists for specific fracture types, particularly hip fractures, a comprehensive synthesis of predictors of functional recovery across different anatomical sites is lacking.

**Objective:**
To comprehensively review the current evidence on predictors of functional recovery following bone fractures and to summarize patient-related, fracture-related, treatment-related, rehabilitation-related, and psychosocial factors associated with functional outcomes.

**Methods:**
A narrative review of the published literature was conducted using peer-reviewed articles indexed in major biomedical databases, including PubMed/MEDLINE, Scopus, Embase, and Google Scholar. Original research articles, systematic reviews, meta-analyses, clinical practice guidelines, and observational studies evaluating predictors of functional recovery following bone fractures were considered. Studies involving adult patients with fractures of the upper limb, lower limb, pelvis, and vertebral column were reviewed. Evidence was synthesized according to major domains influencing recovery.

**Results:**
Current evidence consistently demonstrates that functional recovery after bone fractures is multifactorial. Advanced age, frailty, cognitive impairment, diabetes mellitus, osteoporosis, malnutrition, sarcopenia, and multiple comorbidities are associated with poorer outcomes. Fracture characteristics, including anatomical location, fracture severity, open injuries, intra-articular involvement, and associated soft-tissue damage, significantly influence recovery. Early surgical intervention, stable fixation, prompt mobilization, structured rehabilitation, adequate pain management, and multidisciplinary care improve functional outcomes. Psychosocial factors, including depression, social support, socioeconomic status, and adherence to rehabilitation, also contribute substantially to recovery. Functional assessment tools such as the Lower Extremity Functional Scale (LEFS), Disabilities of the Arm, Shoulder and Hand (DASH) score, Harris Hip Score, Oxford Knee Score, and Short Form-36 (SF-36) are widely used to evaluate recovery. Emerging evidence suggests that predictive models incorporating clinical variables, imaging findings, biomarkers, and machine learning techniques may improve individualized prognostication.

**Conclusion:**
Functional recovery following bone fractures is determined by the interaction of demographic, biological, clinical, psychosocial, and treatment-related factors. Early identification of patients at risk of poor recovery facilitates individualized treatment strategies, optimized rehabilitation, and improved long-term outcomes. Future

prospective multicenter studies should focus on developing validated prediction models applicable across different fracture types to support evidence-based clinical decision-making.

**Keywords:** Bone fractures; Functional recovery; Prognostic factors; Rehabilitation; Fracture healing; Orthopaedic trauma; Functional outcome; Predictive models.

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## INTRODUCTION

Bone fractures represent one of the most common musculoskeletal injuries and constitute a major public health challenge worldwide. They are associated with substantial morbidity, prolonged disability, reduced quality of life, and considerable socioeconomic burden. It is estimated that millions of fractures occur annually across all age groups, with increasing incidence attributable to population aging, osteoporosis, road traffic accidents, sports injuries, occupational trauma, and falls. Although advances in diagnostic imaging, surgical techniques, implant technology, and rehabilitation have significantly improved fracture management over recent decades, functional recovery remains highly variable among individuals. While some patients regain their pre-injury level of function within a few months, others experience persistent pain, impaired mobility, reduced independence, delayed return to work, and long-term disability.[1,2]

Functional recovery following a fracture extends beyond radiographic union and encompasses restoration of physical function, mobility, muscle strength, joint range of motion, activities of daily living, participation in social and occupational roles, and health-related quality of life. Consequently, fracture healing alone should not be considered synonymous with successful clinical recovery. The growing emphasis on patient-reported outcome measures and value-based healthcare has shifted attention toward optimizing functional outcomes rather than solely achieving anatomical union. Commonly used assessment instruments include the Lower Extremity Functional Scale (LEFS), Disabilities of the Arm, Shoulder and Hand (DASH) questionnaire, Harris Hip Score (HHS), Oxford Knee Score (OKS), Short Musculoskeletal Functional Assessment (SMFA), Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), and the Short Form-36 (SF-36), each providing valuable information regarding functional status and quality of life following fracture treatment.[3,4]

Recovery after bone fractures is influenced by a complex interaction of biological, mechanical, clinical, and psychosocial factors. Patient-related characteristics such as age, sex, nutritional status, frailty, osteoporosis, obesity, diabetes mellitus, smoking, cognitive impairment, sarcopenia, and pre-existing comorbidities have been consistently associated with differences in healing potential and functional outcomes. Similarly, fracture-related variables, including anatomical location, fracture severity, displacement, intra-articular extension, open versus closed injuries, associated soft-tissue damage, and neurovascular involvement, significantly influence prognosis. Treatment-related factors—including timing of surgery, choice of fixation, quality of reduction, postoperative pain control, early mobilization, and structured rehabilitation—also play critical roles in determining recovery. In recent years, increasing attention has been directed toward psychological determinants such as depression, anxiety, fear of movement, patient motivation, social support, socioeconomic status, and adherence to rehabilitation, recognizing that these factors substantially affect long-term functional outcomes.[5,6]

Among all fracture types, hip fractures have received the greatest research attention because of their high incidence, particularly among older adults, and their profound impact on mortality, functional independence, and healthcare utilization. Numerous cohort studies and systematic reviews have identified advanced age, poor pre-fracture mobility, cognitive impairment, frailty, malnutrition, delayed surgery, postoperative complications, and inadequate rehabilitation as important predictors of poor functional recovery. Similar prognostic factors have been reported in patients with proximal humerus, distal radius, ankle, tibial, vertebral, and pelvic fractures. However, most published investigations are limited to specific anatomical regions, making it difficult to generalize findings across the broader spectrum of musculoskeletal trauma.[7]

The increasing availability of electronic health records, national trauma registries, multicenter databases, and large administrative datasets has created opportunities to identify prognostic factors across diverse fracture populations. Advances in statistical modeling, machine learning, and artificial intelligence have further enhanced the ability to predict recovery by integrating demographic characteristics, clinical variables, imaging findings, laboratory parameters, and rehabilitation data. Such predictive models have the potential to facilitate individualized treatment planning, optimize resource allocation, improve patient counseling, and support shared clinical decision-making. Nevertheless, considerable heterogeneity persists among published studies regarding outcome measures, follow-up duration, rehabilitation protocols, and methodological quality, limiting the applicability of existing evidence.[8]

Despite the substantial body of literature investigating prognostic factors after specific fractures, comprehensive reviews integrating evidence across different fracture sites remain scarce. Most available reviews focus on hip fractures or individual upper- and lower-limb injuries, leaving an important gap in understanding common determinants of functional recovery applicable to the wider orthopedic population. A broader synthesis of the evidence is essential to identify universal predictors, highlight modifiable risk factors, and guide clinicians in developing personalized rehabilitation strategies.[9]

Therefore, this narrative review aims to comprehensively summarize the current evidence regarding predictors of functional recovery following bone fractures. The review examines patient-related, fracture-related, treatment-related, rehabilitation-related, biological, and psychosocial determinants of recovery across different anatomical fracture types. It also discusses currently available functional outcome measures, emerging predictive models, recent advances in machine learning, existing knowledge gaps, and future directions for research. By integrating contemporary evidence from observational studies, systematic reviews, and clinical guidelines, this review seeks to provide clinicians, researchers, and rehabilitation specialists with an evidence-based overview of factors influencing recovery after bone fractures and to support strategies that improve long-term functional outcomes.

## MATERIALS AND METHODS

A comprehensive literature search was conducted to identify and evaluate published evidence relevant to the objectives of this narrative review. Electronic databases including PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar were searched for relevant articles. The search strategy was developed using combinations of keywords, Medical Subject Headings (MeSH) terms, and related terminology pertaining to functional recovery after bone fracture, with Boolean operators such as "AND" and "OR" used to broaden or refine the search. The search strategy was adapted according to the requirements of individual databases. In addition to database searching, the reference lists of relevant articles and major review papers were manually screened to identify additional publications that may not have been retrieved through the electronic search. Articles were considered eligible for inclusion if they addressed one or more aspects of the review topic and provided clinically or scientifically relevant information. Original research articles, randomized controlled trials, prospective and retrospective observational studies, systematic reviews, meta-analyses, clinical guidelines, consensus statements, and other relevant scholarly publications were considered. Preference was given to recent studies and high-quality evidence, while important older studies were also included when they provided foundational or landmark evidence relevant to the topic. Articles were excluded if they were unrelated to the objectives of the review, duplicated publications, conference abstracts without adequate information, editorials or correspondence without substantive evidence, or publications for which the full text was unavailable. Publications in English were primarily considered for the review. The retrieved articles were initially screened based on their titles and abstracts, following which potentially relevant studies were evaluated through full-text assessment. Information extracted from the selected literature included author and publication details, study design, study population, sample size, relevant exposures or interventions, outcome measures, principal findings, limitations, and clinical implications. The available evidence was critically evaluated and qualitatively synthesized according to the major themes and subtopics relevant to the review. Where findings from different studies were inconsistent, possible explanations related to differences in study populations, methodology, clinical settings, outcome definitions, and follow-up periods were considered. The review also incorporated emerging evidence and recent developments in the field to provide an updated perspective on the topic. The synthesized evidence was subsequently used to identify areas of established knowledge, ongoing controversy, limitations in the existing literature, and important gaps that may guide future research.

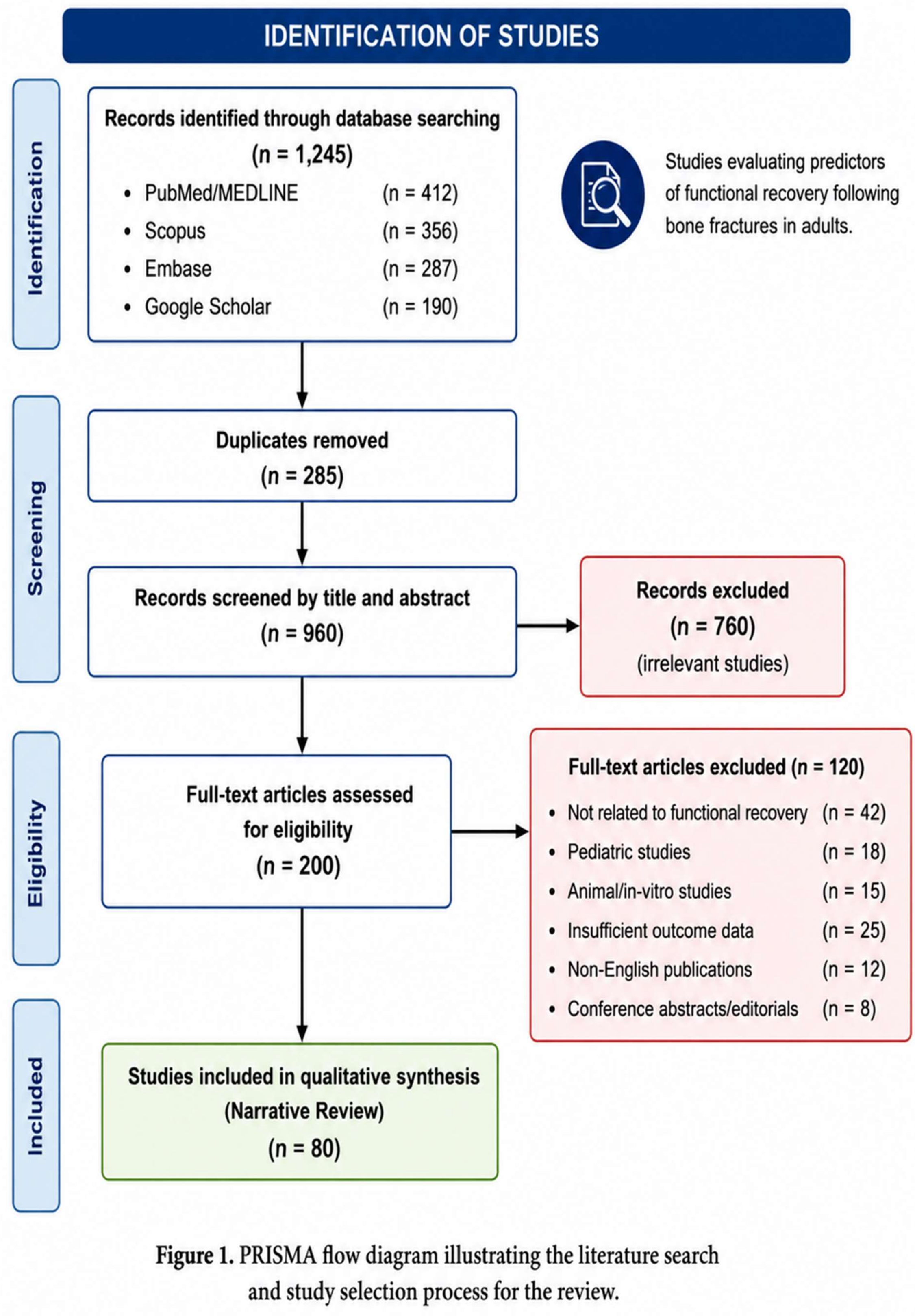


**Figure 1: PRISMA flow diagram showing study selection procedure**

## RESULTS

Functional recovery after bone fractures is multifactorial and depends on patient-related, fracture-related, treatment-related, and psychosocial factors. Older age, frailty, comorbidities, poor nutrition, sarcopenia, and cognitive impairment are associated with delayed or poorer recovery. Fracture severity, location, soft-tissue injury, and intra-articular involvement also influence outcomes. Early stable fixation, timely mobilization, effective pain control, and structured rehabilitation improve functional recovery. Psychosocial support and rehabilitation adherence further contribute to successful outcomes. Standardized functional scores remain valuable for monitoring recovery, while emerging predictive models and machine learning approaches may enable more individualized prognostication and rehabilitation planning.

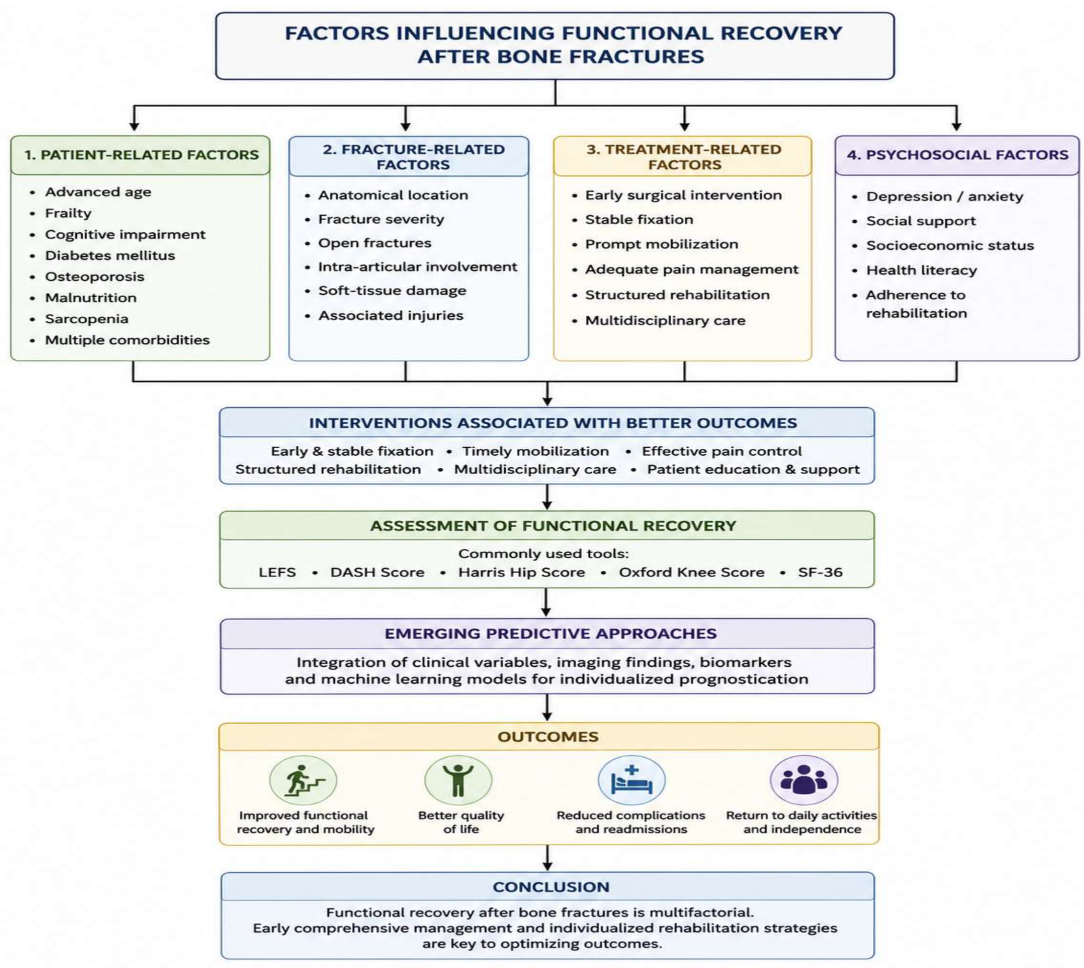


**Figure 2: summary of results**

## LITARATURE REVIEW

### Global Epidemiology of Bone Fractures

Bone fractures are among the most common musculoskeletal injuries worldwide and represent a major cause of disability, healthcare utilization, and socioeconomic burden. Their incidence varies according to age, sex, geographic location, and mechanism of injury. The global increase in population aging, osteoporosis, urbanization, and high-energy trauma has contributed to a steady rise in fracture incidence, making fractures an important public health concern.

According to the Global Burden of Disease (GBD) 2019 study, approximately 178 million new fractures occurred worldwide in 2019, representing a substantial increase compared with previous decades. More than 455 million individuals were living with the consequences of fractures, and fractures accounted for approximately 25.8 million years lived with disability (YLDs), emphasizing their significant contribution to long-term functional impairment and reduced quality of life.[11]

The epidemiology of fractures differs across age groups. In children and adolescents, fractures commonly result from sports injuries, recreational activities, and falls, with the forearm, clavicle, and distal radius being the most frequently affected sites. Among young adults, high-energy trauma such as road traffic accidents, occupational injuries, and sports-related trauma predominates. In contrast, fractures in older adults are mainly associated with low-energy falls and osteoporosis, with hip, vertebral, proximal humerus, and distal radius fractures occurring most frequently.

Hip fractures are considered one of the most serious osteoporotic injuries because of their association with prolonged disability, loss of independence, and increased mortality. Approximately 1.6 million hip fractures occur annually worldwide, and this number is expected to exceed 6 million by 2050 owing to demographic aging. Despite advances in surgical management, many patients fail to regain their pre-fracture level of mobility, and a considerable proportion require long-term rehabilitation or institutional care.

Fragility fractures have become an increasing global health concern. Osteoporosis affects more than 200 million people worldwide and significantly increases the risk of fractures involving the hip, vertebrae, distal radius, and proximal humerus. Women are particularly vulnerable following menopause because of accelerated bone loss, although the incidence of osteoporotic fractures among elderly men is also increasing.[12]

The causes of fractures vary according to socioeconomic development. In high-income countries, falls among older adults are the leading cause of fractures, whereas road traffic accidents, occupational injuries, and interpersonal violence remain major contributors in many low- and middle-income countries. The World Health Organization estimates that road traffic injuries cause approximately 1.19 million deaths annually, with millions of survivors sustaining fractures requiring prolonged orthopedic treatment and rehabilitation.

Fractures also impose a considerable economic burden on healthcare systems. Costs include emergency care, hospitalization, surgical treatment, rehabilitation, long-term follow-up, and indirect expenses related to work absenteeism, caregiver burden, and loss of productivity. Consequently, fractures represent not only a clinical challenge but also a significant socioeconomic issue worldwide.

Although improvements in fracture fixation techniques and rehabilitation have enhanced clinical outcomes, successful fracture healing does not always result in complete functional recovery. Many patients continue to experience pain, reduced mobility, muscle weakness, and limitations in activities of daily living despite radiographic union. Consequently, there is increasing emphasis on identifying predictors of functional recovery that may facilitate individualized treatment planning, optimize rehabilitation strategies, and improve long-term patient outcomes.[13]

With the continued rise in fracture incidence worldwide, understanding the epidemiological trends and determinants of functional recovery has become increasingly important. Identifying patients at risk for poor recovery will enable clinicians to implement targeted interventions aimed at maximizing independence, improving quality of life, and reducing the overall burden of fracture-related disability.[14]

**Biology of Fracture Healing and Functional Recovery**

Fracture healing is a complex and highly regulated biological process that restores the structural integrity and mechanical function of bone following injury. Unlike most tissues, bone has the unique ability to regenerate without scar formation under favorable biological and mechanical conditions. Successful healing depends on the coordinated interaction of inflammatory cells, mesenchymal stem cells, osteoblasts, osteoclasts, vascular endothelial cells, growth factors, and mechanical stability. The efficiency of these processes directly influences functional recovery and the patient's ability to return to pre-injury activities.[15]

Fracture healing occurs through four overlapping phases: inflammation, repair, ossification, and remodeling. Immediately after injury, disruption of blood vessels leads to hematoma formation, which serves as a biological scaffold for healing.

Inflammatory cells release cytokines and growth factors, including interleukins, tumor necrosis factor-α (TNF-α), transforming growth factor-β (TGF-β), bone morphogenetic proteins (BMPs), and vascular endothelial growth factor (VEGF), which recruit mesenchymal stem cells and promote angiogenesis. During the reparative phase, these stem cells differentiate into chondrocytes and osteoblasts, leading to the formation of a soft callus that is gradually replaced by woven bone. Finally, the remodeling phase restores mature lamellar bone and normal bone architecture through coordinated osteoblastic bone formation and osteoclastic bone resorption.[16]

Several biological and mechanical factors influence fracture healing. Advanced age, diabetes mellitus, osteoporosis, smoking, malnutrition, infection, poor vascularity, and severe soft tissue injury can impair bone regeneration and increase the risk of delayed union or non-union. Conversely, adequate blood supply, stable fracture fixation, early mobilization, appropriate nutrition, and effective rehabilitation facilitate successful healing and improve functional outcomes.

Although radiographic union indicates successful bone healing, it does not necessarily reflect complete functional recovery. Functional recovery involves restoration of muscle strength, joint mobility, balance, coordination, gait, and the ability to perform activities of daily living. Prolonged immobilization following fractures may lead to muscle atrophy, joint stiffness, and reduced physical performance, emphasizing the importance of early rehabilitation. Controlled weight-bearing and progressive physiotherapy stimulate bone remodeling, preserve muscle function, and accelerate recovery.[17]

Recent advances in molecular biology have improved understanding of the signaling pathways involved in fracture repair, including BMP, Wnt/β-catenin, and RANKL/osteoprotegerin pathways. These discoveries have led to the development of biological therapies such as growth factors, stem cell therapy, and tissue-engineered scaffolds, although further evidence is required before their widespread clinical use.[18]

**Methods of Assessing Functional Recovery**

Functional recovery following bone fractures is assessed using a combination of clinician-reported, patient-reported, and performance-based outcome measures. These assessments evaluate pain, joint mobility, muscle strength, physical function, activities of daily living, return to work, and health-related quality of life. The selection of an appropriate assessment tool depends on the fracture site, patient characteristics, and study objectives.[19]

Patient-reported outcome measures (PROMs) are widely used because they reflect the patient's perception of recovery and functional status. The Disabilities of the Arm, Shoulder and Hand (DASH) questionnaire is commonly used for upper-limb fractures, while the Lower Extremity Functional Scale (LEFS) is frequently employed for lower-limb injuries. Hip fractures are often evaluated using the Harris Hip Score (HHS) and the Hip Disability and Osteoarthritis Outcome Score (HOOS), whereas knee injuries are commonly assessed using the Oxford Knee Score (OKS) and the Knee Injury and Osteoarthritis Outcome Score (KOOS). Generic quality-of-life instruments such as the Short Form-36 (SF-36) and EuroQol-5 Dimension (EQ-5D) are also widely used to assess overall physical and mental well-being.[20]

Clinician-based outcome measures provide objective assessment of fracture healing and physical function. These include evaluation of pain, joint range of motion, muscle strength, limb alignment, gait, weight-bearing ability, and radiographic evidence of fracture union. Functional independence is frequently assessed using instruments such as the Functional Independence Measure (FIM) and the Barthel Index, particularly among elderly patients and those undergoing rehabilitation.

Performance-based tests complement patient-reported outcomes by objectively measuring physical function. Commonly used assessments include the Timed Up and Go (TUG) test, Six-Minute Walk Test (6MWT), gait speed, chair stand test, and balance assessments. These tests provide valuable information regarding mobility, endurance, balance, and fall risk, especially in older adults recovering from lower-limb fractures.[21]

Assessment of functional recovery should extend beyond radiographic union because complete bone healing does not always correspond to restoration of physical function. Longitudinal evaluation using validated outcome measures at multiple follow-up intervals provides a more comprehensive understanding of recovery and treatment effectiveness. Combining patient-reported, clinician-reported, and performance-based assessments offers the most reliable evaluation of functional recovery and facilitates comparison across clinical studies.[22,23]

**Patient-related Predictors**

Patient-related factors are among the most important determinants of functional recovery following bone fractures. These factors influence bone healing, rehabilitation potential, and the ability to regain pre-injury functional status. Several demographic, clinical, and lifestyle characteristics have consistently been associated with recovery outcomes across different fracture types.[24]

Age is one of the strongest predictors of functional recovery. Increasing age is associated with reduced bone mineral density, impaired muscle strength, delayed fracture healing, multiple comorbidities, and decreased physiological reserve, all of which contribute to slower recovery and reduced functional independence. Elderly patients are also more likely to experience postoperative complications, prolonged hospitalization, and delayed return to activities of daily living.

Pre-injury functional status is another critical determinant of recovery. Patients who are physically active and functionally independent before sustaining a fracture generally achieve better postoperative mobility and quality of life than those with pre-existing physical limitations. Similarly, cognitive function plays an essential role in rehabilitation. Cognitive impairment, dementia, and delirium are associated with poor participation in rehabilitation programs, increased dependency, and inferior long-term functional outcomes.[25,26]

Comorbid medical conditions significantly influence fracture healing and recovery. Diabetes mellitus impairs angiogenesis, collagen synthesis, and bone remodeling, increasing the risk of delayed union and infection. Osteoporosis reduces bone quality and increases susceptibility to fragility fractures, while cardiovascular disease, chronic kidney disease, chronic pulmonary disease, and obesity may delay rehabilitation because of reduced exercise tolerance and increased perioperative risk. Frailty and sarcopenia have also emerged as important predictors of poor functional recovery, particularly among older adults.[27]

Lifestyle factors further affect recovery following fractures. Smoking has consistently been associated with delayed fracture healing, non-union, and poorer functional outcomes because nicotine impairs blood flow and osteoblast function. Excessive alcohol consumption, poor nutritional status, vitamin D deficiency, and inadequate protein intake negatively influence bone regeneration and muscle recovery. Conversely, patients with good nutritional status and healthy lifestyle habits generally demonstrate faster recovery and improved rehabilitation outcomes.[28]

Psychological health is increasingly recognized as an important predictor of functional recovery. Depression, anxiety, fear of falling, and reduced self-efficacy may limit participation in rehabilitation and delay return to normal activities. In contrast, strong social support, positive coping strategies, and adherence to prescribed rehabilitation programs are associated with better functional outcomes and improved quality of life.

**Fracture-related Predictors**

Fracture-related characteristics play a crucial role in determining the rate of bone healing and subsequent functional recovery. The anatomical location, severity of injury, fracture configuration, soft tissue involvement, and associated complications influence both the biological healing process and rehabilitation outcomes.

The site of the fracture is one of the strongest predictors of functional recovery. Fractures involving weight-bearing bones, such as the hip, femur, tibia, and pelvis, are generally associated with prolonged rehabilitation and greater functional impairment than fractures of the upper extremity. Hip fractures, in particular, are linked to reduced mobility, loss of independence, and increased long-term disability, especially among older adults.

Fracture type and severity also influence recovery. Open fractures, comminuted fractures, intra-articular fractures, segmental fractures, and fractures associated with extensive soft tissue injury have a higher risk of delayed union, non-union, infection, and joint stiffness compared with simple closed fractures. High-energy injuries often result in greater soft tissue damage and prolonged recovery than low-energy fragility fractures.

Fracture stability is another important determinant of healing. Stable fracture patterns generally achieve earlier union and permit early mobilization, whereas unstable fractures often require prolonged immobilization or complex surgical fixation, delaying rehabilitation and increasing the risk of functional limitations. Similarly, fracture displacement and poor anatomical reduction may alter joint biomechanics, resulting in chronic pain, reduced range of motion, and post-traumatic osteoarthritis.

Soft tissue injury substantially affects functional outcomes. Damage to muscles, tendons, ligaments, nerves, and blood vessels compromises vascularity and delays healing, while increasing the likelihood of infection and prolonged disability. Open fractures with extensive soft tissue loss often require staged reconstructive procedures, further extending the rehabilitation period.[29]

The occurrence of fracture-related complications is consistently associated with poorer functional recovery. Delayed union, non-union, malunion, implant failure, infection, avascular necrosis, and post-traumatic arthritis may result in persistent pain, repeated surgical interventions, and long-term impairment of physical function. Early recognition and appropriate management of these complications are essential for optimizing patient outcomes.

### Surgical Predictors

Surgical management plays a pivotal role in determining functional recovery following bone fractures. Appropriate surgical planning, timely intervention, stable fixation, and restoration of anatomical alignment facilitate fracture healing, enable early mobilization, and reduce the risk of complications. Conversely, inadequate fixation or delayed intervention may compromise both biological healing and long-term functional outcomes.[30]

The timing of surgery is an important predictor of recovery. Early surgical fixation, particularly within 24–48 hours for hip and long-bone fractures, has been associated with reduced postoperative complications, shorter hospital stay, earlier mobilization, and improved functional outcomes. Delayed surgery may increase the risk of infection, prolonged immobilization, thromboembolic events, and muscle deconditioning, especially in elderly patients. The choice of fixation method also influences recovery. Internal fixation using plates, screws, intramedullary nails, or locking constructs provides stable fracture fixation and allows early weight-bearing in appropriately selected patients. In contrast, external fixation is generally reserved for open fractures, severe soft tissue injuries, or damage-control orthopedics and may require staged definitive procedures. Arthroplasty is often preferred for selected proximal femoral fractures in elderly patients because it permits earlier mobilization and functional rehabilitation compared with internal fixation in appropriate clinical settings.[31,32]

Achieving accurate anatomical reduction is essential, particularly for intra-articular fractures. Poor reduction may alter joint congruity, increase mechanical stress, and predispose patients to chronic pain, stiffness, post-traumatic osteoarthritis, and impaired function. Preservation of soft tissue integrity and blood supply during surgery is equally important, as excessive surgical dissection can compromise fracture healing and increase the risk of infection and delayed union.[33,34]

Postoperative complications significantly affect functional recovery. Surgical site infection, implant failure, loss of fixation, malunion, non-union, and avascular necrosis frequently necessitate revision procedures and prolong rehabilitation. Effective perioperative pain management, early postoperative physiotherapy, thromboprophylaxis, and multidisciplinary care contribute to improved recovery and earlier return to activities of daily living.[34]

### Rehabilitation Predictors

Rehabilitation is a key determinant of functional recovery following bone fractures, as it facilitates restoration of mobility, muscle strength, joint function, and independence. The timing, intensity, and adherence to rehabilitation programs significantly influence recovery outcomes, regardless of fracture type or treatment modality.

Early mobilization is one of the most important predictors of successful recovery. Initiating physiotherapy soon after fracture stabilization or surgical fixation helps prevent muscle atrophy, joint stiffness, venous thromboembolism, and functional decline. Patients who begin weight-bearing and supervised rehabilitation early generally achieve faster recovery, shorter hospital stays, and improved long-term functional outcomes compared with those undergoing prolonged immobilization.[35]

Structured rehabilitation programs focusing on range-of-motion exercises, progressive muscle strengthening, gait training, balance exercises, and functional task practice have consistently demonstrated benefits in improving mobility and activities of daily living. Individualized rehabilitation plans that consider patient age, fracture type, comorbidities, and baseline functional status are associated with better adherence and superior clinical outcomes.

Patient participation and adherence are equally important predictors of recovery. Regular attendance at physiotherapy sessions, compliance with home exercise programs, and active engagement in rehabilitation contribute significantly to improved functional performance. In contrast, poor adherence, prolonged inactivity, and fear of movement are associated with delayed recovery and persistent disability.

Multidisciplinary rehabilitation involving orthopedic surgeons, physiotherapists, occupational therapists, rehabilitation physicians, nurses, nutritionists, and psychologists further enhances functional outcomes. Comprehensive rehabilitation addresses not only physical impairments but also nutritional status, pain management, psychological well-being, and social reintegration, particularly among elderly patients recovering from major fractures.

### Nutritional and Metabolic Predictors

Nutritional and metabolic status plays a fundamental role in fracture healing and functional recovery. Adequate intake of energy, protein, vitamins, and minerals is essential for collagen synthesis, bone mineralization, muscle maintenance, and tissue repair. Nutritional deficiencies and metabolic disorders can delay fracture healing, impair rehabilitation, and increase the risk of complications.[36]

Protein-energy malnutrition is one of the most important predictors of poor functional recovery, particularly among older adults. Inadequate protein intake contributes to muscle wasting, reduced muscle strength, impaired immune function, and delayed wound healing, resulting in prolonged rehabilitation and reduced mobility. Low serum albumin and prealbumin levels have also been associated with increased postoperative complications, delayed recovery, and higher mortality following hip fractures.

Vitamin D and calcium are essential for bone metabolism and mineralization. Vitamin D deficiency is common among elderly patients with fragility fractures and has been associated with impaired bone healing, muscle weakness, increased fall risk, and poorer functional outcomes. Adequate calcium intake, together with vitamin D supplementation when indicated, supports fracture healing and helps maintain bone mineral density.

Metabolic disorders such as diabetes mellitus and osteoporosis significantly influence fracture healing. Diabetes impairs angiogenesis, collagen synthesis, and bone remodeling, increasing the risk of delayed union, infection, and non-union. Osteoporosis reduces bone quality and mechanical strength, predisposing patients to fragility fractures and delayed functional recovery. Other conditions, including chronic kidney disease and endocrine disorders, may further impair bone metabolism and prolong rehabilitation.[37]

Recent evidence also highlights the importance of sarcopenia, characterized by the loss of skeletal muscle mass and strength, as an independent predictor of poor functional recovery. Patients with sarcopenia often experience slower rehabilitation, reduced mobility, and lower rates of return to independent living. Nutritional optimization combined with resistance exercise has been shown to improve muscle function and enhance recovery following fractures.

**Psychological and Socioeconomic Predictors**

Psychological and socioeconomic factors have emerged as important determinants of functional recovery following bone fractures. In addition to biological healing, successful recovery depends on the patient's mental health, motivation, social support, educational status, and access to rehabilitation services. These factors influence adherence to treatment, participation in rehabilitation, and the ability to regain functional independence.

Psychological disorders such as depression, anxiety, fear of falling, and pain catastrophizing have been consistently associated with poorer functional outcomes. Patients experiencing psychological distress are less likely to participate actively in rehabilitation programs, resulting in delayed mobility, prolonged disability, and reduced quality of life. Cognitive impairment and dementia further complicate recovery by limiting compliance with postoperative instructions and rehabilitation exercises, particularly among older adults.[32]

Patient motivation and self-efficacy also play a significant role in rehabilitation. Individuals with greater confidence in their ability to recover are more likely to adhere to prescribed exercise programs and achieve earlier functional improvement. Conversely, fear of reinjury and reduced confidence may lead to avoidance of physical activity, delayed weight-bearing, and persistent functional limitations.

Social support is another important predictor of recovery. Assistance from family members, caregivers, and healthcare professionals facilitates adherence to rehabilitation, medication compliance, and regular follow-up. Patients with strong social support generally demonstrate better mobility, greater independence in activities of daily living, and improved health-related quality of life compared with socially isolated individuals.

Socioeconomic status also influences functional recovery. Lower income, limited education, unemployment, inadequate health insurance, and poor access to rehabilitation services are associated with delayed treatment, reduced participation in physiotherapy, and poorer long-term outcomes. Geographic disparities, particularly in rural and resource-limited settings, may further restrict access to specialized orthopedic care and rehabilitation facilities.

A multidisciplinary approach that incorporates psychological assessment, patient education, counseling, and social support alongside medical and surgical treatment can improve rehabilitation adherence and optimize functional recovery. Addressing modifiable psychological and socioeconomic barriers is therefore essential for achieving successful long-term outcomes following bone fractures.[35]

**Biomarkers of Recovery**

Biomarkers have gained increasing attention as potential tools for predicting fracture healing and functional recovery. They provide objective information on bone formation, bone resorption, inflammation, and tissue repair, enabling clinicians to identify patients at risk of delayed healing or poor functional outcomes. Although no single biomarker has been universally adopted for routine clinical practice, several biochemical markers have shown promising prognostic value.

Inflammatory biomarkers play a critical role during the early phase of fracture healing. C-reactive protein (CRP), erythrocyte sedimentation rate (ESR), interleukin-6 (IL-6), and tumor necrosis factor-α (TNF-α) increase immediately after injury as part of the inflammatory response. Persistent elevation of these markers beyond the expected healing period may indicate infection, delayed healing, or impaired recovery.[37]

Markers of bone formation, including bone-specific alkaline phosphatase (BALP), osteocalcin, and procollagen type I N-terminal propeptide (PINP), reflect osteoblastic activity and new bone formation. Conversely, markers of bone resorption such as C-terminal telopeptide of type I collagen (CTX) and N-terminal telopeptide (NTX) indicate osteoclastic activity and bone remodeling. Monitoring these biomarkers may help assess the progression of fracture healing, although their routine clinical use remains limited.

Vitamin D and calcium metabolism are also important determinants of bone repair. Low serum 25-hydroxyvitamin D levels have been associated with impaired fracture healing, reduced bone mineralization, muscle weakness, and poorer functional recovery. Similarly, abnormalities in parathyroid hormone and calcium homeostasis may adversely affect bone remodeling and increase the risk of delayed union.

Nutritional biomarkers such as serum albumin, prealbumin, and hemoglobin provide indirect information regarding nutritional status and physiological reserve. Hypoalbuminemia and anemia have been associated with increased postoperative complications, delayed rehabilitation, prolonged hospital stay, and poorer functional outcomes, particularly among elderly patients with hip fractures.[31]

Recent advances in molecular biology have identified novel biomarkers, including microRNAs, circulating mesenchymal stem cells, exosomes, and bone morphogenetic proteins (BMPs), as potential predictors of fracture healing. Although these biomarkers have demonstrated encouraging results in experimental and early clinical studies, further large-scale prospective investigations are required before they can be incorporated into routine clinical practice.

**Machine Learning and Prediction Models**

The increasing availability of electronic health records, national trauma registries, and large clinical databases has facilitated the development of prediction models for functional recovery following bone fractures. These models integrate multiple patient, fracture, treatment, and rehabilitation variables to estimate recovery trajectories, identify patients at risk of poor outcomes, and support personalized clinical decision-making.

Conventional prediction models primarily rely on multivariable regression analysis to identify independent predictors of recovery. Variables such as age, sex, pre-injury functional status, fracture type, comorbidities, cognitive function, surgical timing, nutritional status, and rehabilitation adherence have consistently demonstrated predictive value. Several prognostic models developed for hip fractures have shown moderate to good accuracy in predicting mobility, functional independence, mortality, and quality of life.[39]

Recent advances in artificial intelligence (AI) and machine learning (ML) have enabled the development of more sophisticated prediction models capable of analyzing large and complex datasets. Supervised learning algorithms, including random forests, support vector machines, gradient boosting, and artificial neural networks, can identify complex nonlinear relationships among clinical variables that may not be detected using conventional statistical methods. These models have demonstrated promising performance in predicting fracture healing, postoperative complications, hospital readmission, functional recovery, and the risk of delayed union or non-union.

Machine learning models can integrate diverse sources of information, including demographic characteristics, radiographic findings, laboratory biomarkers, surgical variables, rehabilitation progress, and patient-reported outcome measures, to generate individualized risk estimates. Such models may assist clinicians in selecting optimal treatment strategies, planning rehabilitation intensity, and counseling patients regarding expected recovery.[40]

Despite these advances, several challenges limit the routine clinical implementation of machine learning models. Many published studies are based on retrospective single-center datasets with relatively small sample sizes, limiting their generalizability. In addition, differences in outcome measures, missing data, lack of external validation, and limited model interpretability remain important concerns. Future research should focus on developing robust multicenter prediction models using standardized datasets and prospective validation to improve their clinical applicability.[41]

## EVIDENCE BY FRACTURE TYPE[42,43]

### Hip fractures

Hip fractures are the most extensively studied fractures with respect to functional recovery, particularly among older adults. Systematic reviews consistently identify advanced age, poor pre-fracture mobility, cognitive impairment, frailty, malnutrition, delayed surgery, and multiple comorbidities as major predictors of poor functional outcomes. Early surgical intervention, multidisciplinary orthogeriatric care, and structured rehabilitation significantly improve mobility, independence in activities of daily living, and quality of life. Despite advances in treatment, approximately one-third of patients fail to regain their pre-fracture functional status, emphasizing the importance of early risk stratification and individualized rehabilitation.

### Proximal femur fractures

Functional recovery following proximal femur fractures depends on fracture stability, quality of surgical fixation, and postoperative rehabilitation. Independent predictors of poor recovery include advanced age, osteoporosis, sarcopenia, delayed weight-bearing, postoperative complications, and reduced pre-injury functional status. Studies have demonstrated that early mobilization and comprehensive rehabilitation programs improve walking ability, reduce dependency, and facilitate return to independent living.

### Distal radius fractures

Distal radius fractures are among the most common upper-limb injuries, particularly in elderly women with osteoporosis. Functional outcomes are generally favorable; however, recovery may be influenced by fracture displacement, intra-articular involvement, associated soft tissue injury, and treatment modality. Age, baseline hand function, rehabilitation adherence, and early restoration of wrist mobility are important determinants of recovery. Patient-reported outcome measures such as the Disabilities of the Arm, Shoulder and Hand (DASH) questionnaire are commonly used to assess functional improvement.

### Proximal humerus fractures

Recovery after proximal humerus fractures is influenced by fracture complexity, bone quality, treatment approach, and patient-related factors. Recent systematic reviews have highlighted age, baseline shoulder function, pain severity, psychological well-being, and rehabilitation adherence as important prognostic factors. Both operative and non-operative management can provide satisfactory outcomes in appropriately selected patients, although early physiotherapy is essential for restoring shoulder mobility and reducing long-term disability.

### Tibial fractures

Tibial fractures frequently result from high-energy trauma and are often associated with significant soft tissue injury. Functional recovery may be prolonged because of delayed union, non-union, infection, and impaired weight-bearing. Predictors of poor outcomes include open fractures, severe soft tissue damage, smoking, diabetes mellitus, and postoperative complications. Stable fixation combined with early rehabilitation and gradual weight-bearing contributes to improved functional recovery and earlier return to work.

### Ankle fractures

Ankle fractures generally have a favourable prognosis; however, recovery may be affected by fracture severity, syndesmotic injury, obesity, diabetes, and postoperative stiffness. Early mobilization, supervised physiotherapy, and restoration of joint congruity are associated with improved range of motion and functional outcomes. Persistent pain and post-traumatic osteoarthritis remain important causes of long-term disability, particularly following complex intra-articular injuries.

### Vertebral fractures

Vertebral compression fractures, most commonly associated with osteoporosis, contribute substantially to chronic pain, spinal deformity, reduced mobility, and diminished quality of life. Functional recovery depends on pain control, vertebral stability, bone health optimization, and rehabilitation. Advanced age, multiple vertebral fractures, severe osteoporosis, and delayed diagnosis are associated with poorer outcomes. Exercise therapy, osteoporosis treatment, and multidisciplinary rehabilitation play important roles in improving mobility and reducing future fracture risk.

### Pelvic fractures

Pelvic fractures encompass a wide spectrum of injuries ranging from low-energy fragility fractures in older adults to high-energy polytrauma in younger individuals. Functional recovery is influenced by fracture stability, associated visceral and neurovascular injuries, surgical management, and rehabilitation intensity. Elderly patients with pelvic fragility fractures often experience prolonged functional impairment because of frailty, osteoporosis, and multiple comorbidities. Early mobilization, multidisciplinary rehabilitation, and comprehensive geriatric care have been shown to improve mobility and functional independence.

| Author (Year) | Study design | Fracture type | Sample | Key predictors / interventions | Major findings |
|---|---|---|---|---|---|
| Xu (2019) | Systematic review | Hip | 57 studies | Age, cognition, mobility | Poor baseline status predicts poorer recovery |
| Araiza-Nava (2022) | Systematic review | Hip | 52 studies | Frailty, nutrition | Early surgery and rehabilitation improve recovery |
| Sheehan (2018) | Systematic review | Hip | 43 studies | Age, cognition | Baseline functional status is the strongest predictor |
| van der Sijp (2020) | Systematic review | Proximal femur | 30 studies | Frailty, sarcopenia | Frailty and sarcopenia are associated with delayed recovery |
| Baker (2023) | Systematic review | Proximal humerus | 35 studies | Pain, psychological factors | Psychological factors affect recovery |
| MacIntyre (2016) | Review | Distal radius | Multiple | Age, rehabilitation | Early mobilization supports functional recovery |
| Bhandari (2008) | Randomized controlled trial | Tibia | 1,319 | Fixation strategy | Stable fixation improves functional outcomes |
| Handoll (2021) | Cochrane review | Hip | 40+ trials | Rehabilitation | Rehabilitation improves mobility |
| Magaziner (2019) | Randomized controlled trial | Hip | 210 | Home-based rehabilitation | Home rehabilitation improves activities of daily living |

**Table 1. Summary of Evidence on Predictors of Functional Recovery Following Fractures**

## DISCUSSION

Functional recovery following bone fractures is a complex and multifactorial process influenced by the interaction of patient-related, fracture-related, treatment-related, rehabilitation-related, and psychosocial factors. Although successful fracture healing is commonly assessed by radiological union, restoration of functional independence, mobility, and quality of life represents the ultimate goal of fracture management. The evidence reviewed in this article suggests that recovery cannot be predicted by fracture characteristics alone, emphasizing the need for a comprehensive, patient-centered approach.[31.33]

Among patient-related factors, increasing age consistently emerges as one of the strongest predictors of delayed functional recovery. Older adults often experience reduced bone quality, sarcopenia, frailty, and multiple comorbidities that impair both fracture healing and rehabilitation. However, chronological age alone should not be considered the sole determinant of prognosis. Pre-fracture functional status, baseline mobility, nutritional status, and overall physical fitness often provide more meaningful information regarding a patient's recovery potential. Patients who are physically active and independent before injury generally regain function more rapidly than those with limited mobility or pre-existing disability.

Fracture characteristics also play a critical role in determining outcomes. The anatomical location, severity, degree of displacement, comminution, intra-articular involvement, and associated soft-tissue injury directly influence the duration of recovery and long-term functional performance. Lower-extremity fractures, particularly those involving the hip, femur, tibia, and ankle, frequently result in prolonged impairment because they affect weight-bearing and gait. Similarly, intra-articular fractures may predispose patients to joint stiffness, chronic pain, and post-traumatic osteoarthritis despite satisfactory radiological healing.[36]

Treatment-related factors significantly influence recovery. Appropriate fracture stabilization, restoration of anatomical alignment, and early management of associated soft-tissue injuries contribute to improved functional outcomes. While surgical fixation allows early mobilization in many patients, treatment decisions should be individualized according to fracture type, patient characteristics, and overall health status. Equally important is effective postoperative pain management, which facilitates participation in rehabilitation and reduces the risk of prolonged immobility and functional decline.

Rehabilitation remains one of the most important modifiable predictors of recovery. Early mobilization, structured physiotherapy, progressive strengthening exercises, and balance training help restore joint mobility, muscle strength, and functional independence. Delayed or inadequate rehabilitation may result in persistent stiffness, muscle atrophy, and reduced physical performance even after complete fracture union. Therefore, rehabilitation programs should be individualized based on fracture stability, healing progress, and patient-specific functional goals.

Psychological and social factors are increasingly recognized as important determinants of recovery. Depression, anxiety, fear of falling, fear of reinjury, and reduced self-efficacy may decrease patient participation in rehabilitation and delay return to normal activities. Similarly, inadequate family support, financial constraints, and limited access to rehabilitation services may negatively influence recovery, particularly in older adults and individuals from resource-limited settings. These findings highlight the importance of multidisciplinary fracture care involving orthopedic surgeons, physiotherapists, physicians, psychologists, nutritionists, and social support services when appropriate.[37,39]

An important observation from the available literature is that radiological healing does not always correlate with functional recovery. Many patients demonstrate complete fracture union while continuing to experience pain, reduced muscle strength, impaired mobility, or limitations in activities of daily living. Consequently, functional outcome assessment should include validated patient-reported outcome measures, mobility assessments, and quality-of-life evaluations in addition to conventional radiographic findings. Such comprehensive assessment provides a more accurate representation of patient recovery and treatment success.

Recent advances in predictive modeling, artificial intelligence, and biomarker research offer promising opportunities for individualized prognostication. Machine-learning algorithms that combine demographic characteristics, fracture features, imaging findings, laboratory parameters, and functional assessments may improve the early identification of patients at risk for delayed recovery. However, these technologies require further validation before widespread clinical implementation and should complement rather than replace clinical judgment.

## CLINICAL IMPLICATIONS

Identification of predictors of functional recovery is essential for optimizing the management of patients with bone fractures. Early recognition of individuals at risk of poor recovery allows clinicians to implement personalized treatment strategies and allocate rehabilitation resources more effectively. Comprehensive assessment should consider patient-related, fracture-related, surgical, nutritional, psychological, and rehabilitation factors rather than relying solely on radiographic fracture healing.

Early surgical fixation, when indicated, followed by structured rehabilitation and timely mobilization, plays a crucial role in restoring mobility and functional independence. Optimization of modifiable risk factors, including nutritional deficiencies, osteoporosis, diabetes, smoking, and psychological disorders, can further improve fracture healing and long-term outcomes. The use of validated functional outcome measures enables regular monitoring of recovery and facilitates timely modifications to treatment plans.

A multidisciplinary approach involving orthopedic surgeons, physiotherapists, rehabilitation specialists, nutritionists, geriatricians, and mental health professionals is particularly beneficial for elderly patients and those with complex fractures. In addition, emerging prediction models and machine learning algorithms offer promising opportunities for individualized risk stratification and rehabilitation planning, although further validation is required before widespread clinical implementation.

## FUTURE RESEARCH DIRECTIONS

Future research should focus on developing robust and externally validated prediction models that integrate patient-related, fracture-related, surgical, rehabilitation, nutritional, and psychosocial factors. Large multicenter prospective studies with standardized functional outcome measures are needed to improve the accuracy and generalizability of prognostic models across different fracture types.

The integration of advanced imaging, biochemical biomarkers, wearable technologies, and artificial intelligence offers promising opportunities for personalized prediction of functional recovery. Further studies should evaluate the clinical utility of machine learning algorithms in guiding treatment decisions and rehabilitation planning. In addition, greater emphasis should be placed on patient-reported outcome measures, long-term quality of life, and cost-effectiveness analyses to better understand recovery beyond radiographic fracture union.

Future research should also explore targeted rehabilitation strategies, nutritional interventions, and multidisciplinary care models to identify the most effective approaches for optimizing functional recovery. These efforts will contribute to personalized fracture management and improve long-term outcomes for patients with musculoskeletal injuries.

## CONCLUSION

Functional recovery following bone fractures is influenced by a complex interplay of patient-related, fracture-related, surgical, nutritional, psychological, and rehabilitation factors. Early identification of these predictors enables individualized treatment, timely rehabilitation, and improved clinical outcomes. Emerging technologies, including biomarkers and machine learning, offer promising opportunities for personalized fracture care, although further validation is needed. A multidisciplinary, patient-centered approach remains essential for optimizing recovery, restoring functional independence, and improving quality of life after fractures.

## AUTHOR CONTRIBUTIONS

Author 1 contributed to the conception and design of the review, literature search, data collection, analysis and interpretation of the available evidence, and preparation of the initial manuscript. Author 2 contributed to the literature search, critical evaluation and synthesis of the relevant literature, and revision of the manuscript for important intellectual content. Author 3 contributed to the overall supervision of the work, critical review of the manuscript, interpretation of the findings, and final approval of the version to be published. All authors reviewed and approved the final manuscript and agree to be accountable for all aspects of the work.

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