Vol. 5 No. 1 (2026)

Pakistan Journal of Medical & Cardiological Review

https://pakjmcr.com/index.php/1/about

Online ISSN 3007-2387

Print ISSN 3007-2379

Nutritional Biomarkers as Predictors of Rehabilitation Success in Musculoskeletal Disorders: Bridging Nutrition Science and Physiotherapy

Zarish Fatima Zaidi* (Corresponding Author)
Faculty of Pharmacy and Allied Health Sciences, Department of Nutrition (Human Nutrition and Dietetics), University of Sialkot (USKT).
Email: zarishzaidi98@gmail.com ORCID: https://orcid.org/0009-0002-3740-9785

Shiza Fatima Zaidi
Faculty of Pharmacy and Allied Health Sciences, Department of Physiotherapy and Rehabilitation, University of Sialkot (USKT).
Email: shizazaidi7@gmail.com ORCID: https://orcid.org/0009-0005-4949-4034

Sameen Ahsan
Faculty of Knowledge Unit of Health Sciences, University of Management and Technology Sialkot.
Email: sameenahsan123@gmail.com

Dua Afzal Butt
University of Sialkot (USKT), Faculty of Pharmacy and Allied Health Sciences, Department of Physiotherapy and Rehabilitation, Sialkot, Pakistan.
Email: buttdua129@gmail.com ORCID: https://orcid.org/0009-0000-3604-8733

Sundus Ghayas Munir
University of Sialkot, Doctor of Physiotherapy (DPT) Graduate
Email: sundusghayasmunir@gmail.com
ORCID number: 0009-0008-8303-9141

Dil Nasheen Zahr
University of Sargodha.
Email: znaqvi572@gmail.com
ORCID: https://orcid.org/0009-0004-4490-4252

Author Details

Keywords: Nutritional biomarkers; Musculoskeletal disorders; Rehabilitation outcomes; Precision nutrition; Vitamin D; Muscle recovery; Inflammation; Personalized rehabilitation

Received on 25 Jan 2026
Accepted on 28 Feb 2026
Published on 10 Mar 2026

Corresponding E-mail & Author*:

Zarish Fatima Zaidi*
Faculty of Pharmacy and Allied Health Sciences, Department of Nutrition (Human Nutrition and Dietetics), University of Sialkot (USKT).
Email: zarishzaidi98@gmail.com

Abstract

Musculoskeletal disorders (MSDs) are a leading cause of global disability, with rehabilitation outcomes varying considerably among individuals despite advances in physiotherapy-based interventions. Emerging evidence highlights the importance of nutritional status in regulating tissue repair, muscle adaptation, inflammation, and functional recovery. This review explores the role of nutritional biomarkers as predictive tools for optimizing rehabilitation outcomes in individuals with musculoskeletal conditions. The biological interactions between nutrition and recovery processes are discussed, emphasizing protein metabolism, bone remodeling, connective tissue healing, inflammation regulation, and oxidative stress control. Key nutritional biomarkers, including vitamin D status, protein-related indicators, iron parameters, omega-3 fatty acid profiles, and micronutrient markers, are evaluated for their potential association with muscle function, bone healing, and rehabilitation progress. Evidence across osteoarthritis, post-fracture recovery, sarcopenia, and sports injury rehabilitation demonstrates that nutritional assessment can provide valuable insights for individualized intervention planning. Although biomarker-guided rehabilitation represents a promising approach toward precision care, challenges including lack of standardized biomarker panels, clinical validation, cost limitations, and insufficient longitudinal evidence restrict widespread implementation. Future research should focus on establishing clinically applicable biomarker frameworks to integrate nutritional assessment with personalized rehabilitation strategies. Nutritional biomarker-guided approaches may represent a transformative pathway for improving recovery prediction, optimizing therapeutic decisions, and enhancing patient-centered musculoskeletal care.

Introduction

Musculoskeletal disorders (MSDs) represent a major global health burden, ranking as the third leading cause of disability worldwide and the largest single cause of years lived with disability (Barrero & Caban-Martinez, 2021; Sivan et al., 2019). In the United States alone, MSDs affect over 121 million people and account for the highest disability rates among all disease groups (Nguyen et al., 2025). The prevalence is particularly high among women and peaks at ages 65-69, with developed countries experiencing the greatest burden due to aging populations (Matkerimova et al., 2026). Common conditions include osteoarthritis, low back pain, neck pain, osteoporosis, and sarcopenia, which collectively diminish quality of life and strain healthcare systems (Nguyen et al., 2025; Barrero & Caban-Martinez, 2021). Risk factors encompass obesity, occupational exposures, and sedentary lifestyles, with healthcare professionals facing particularly high risks. The economic impact is substantial, involving increased healthcare costs and lost productivity (Matkerimova et al., 2026).

Current musculoskeletal rehabilitation emphasizes a shift from traditional biomedical approaches to comprehensive, patient-centered care incorporating biopsychosocial understanding (Hutting et al., 2021). Exercise-based physiotherapy remains the primary therapeutic intervention, with evidence supporting progressive loading, neuromuscular re-training, and structured progression for tissue adaptation and functional restoration (Shankar et al., 2026). Modern rehabilitation models advocate for criteria-based rather than time-based approaches, utilizing objective measures of strength symmetry,

movement quality, and psychological readiness (Shankar et al., 2026; Cranswick et al., 2025).

Despite these advances, significant variation in patient recovery persists. Current rehabilitation interventions provide only modest short-term benefits, highlighting the need for better understanding of intervention mechanisms and patient stratification based on outcome risk (Cashin & Sterling, 2025). The inconsistencies in rehabilitation model structure and implementation practices contribute to variable outcomes (Cranswick et al., 2025). Optimizing rehabilitation requires enhanced patient-centeredness, individualized progression, and improved identification of patients most likely to benefit from specific interventions (Hutting et al., 2021; Cashin & Sterling, 2025).

Nutrition plays a fundamental role in musculoskeletal rehabilitation by supporting tissue repair, inflammation regulation, and functional recovery. Adequate energy availability is essential for immune function and regenerative processes, while higher protein intake (2.0-3.0 g/kg body weight) distributed throughout the day helps preserve muscle mass and enhance recovery (Escobar et al., 2026; Nikolova et al., 2026). Specific nutrients demonstrate targeted benefits: omega-3 fatty acids (4,000 mg/day) and antioxidants modulate inflammation, while vitamins D and C support collagen synthesis and bone health (Escobar et al., 2026; Nikolova et al., 2026). Evidence-based supplementation including whey protein, hydrolyzed collagen, creatine, and HMB can provide additional benefits when individualized (Escobar et al., 2026; Nikolova et al., 2026). The integration of physiotherapy and nutrition creates synergistic effects that accelerate healing, improve muscle strength, and reduce rehabilitation duration (Sarkar et al., 2026). However, nutritional interventions must be carefully timed and targeted to specific patient populations for optimal functional outcomes (Gubajdullin et al., 2022).

Nutritional biomarkers represent measurable indicators of biological processes that can objectively assess dietary intake and physiological responses, overcoming limitations of self-reported dietary assessments (Picó et al., 2019). These biomarkers offer significant potential for improving rehabilitation outcomes by enabling personalized intervention strategies based on individual physiological profiles (Prerana et al., 2024). Research demonstrates that nutritional status serves as a critical predictor of rehabilitation success. Malnourished patients show reduced functional abilities on admission and discharge, experience slower rehabilitation gains, and face nearly four times greater odds of functional decline during treatment (Lambert et al., 2019). This evidence supports the integration of nutritional biomarkers into comprehensive assessment protocols. The concept extends to precision rehabilitation medicine, where multimodal biomarkers including molecular, imaging, and computational indicators can guide individualized treatment approaches (Nartea et al., 2025). Such biomarkers enable clinicians to identify patients with specific deficiencies, analyze physiological responses to interventions, and formulate personalized recommendations to optimize rehabilitation outcomes across diverse conditions (Picó et al., 2019).

This review aims to examine the potential role of nutritional biomarkers in predicting and improving rehabilitation outcomes in individuals with musculoskeletal disorders. It explores the relationship between nutritional status and recovery processes, with particular emphasis on biomarkers associated with muscle function, bone health, inflammation, and tissue repair. The review discusses the relevance of vitamin D, protein-related indicators, iron status, omega-3 fatty acids, and micronutrient biomarkers across various rehabilitation conditions, including osteoarthritis, fracture healing, sarcopenia, and sports-related injuries. Furthermore, it highlights the emerging application of biomarker-guided nutritional approaches in personalized rehabilitation and identifies current limitations and future directions for their integration into clinical practice.

Biological Connection Between Nutrition and Musculoskeletal Recovery

Nutrition plays a crucial role in musculoskeletal recovery through multiple biological mechanisms. Adequate energy availability is essential for supporting immune function and regenerative processes, while higher protein intake helps preserve muscle mass and enhance functional recovery. Key nutrients including omega-3 fatty acids, dietary antioxidants, and micronutrients such as vitamins D and C are vital for modulating inflammation, collagen synthesis, and bone health (Escobar et al., 2026). The relationship between nutrition and chronic musculoskeletal pain involves underlying mechanisms of inflammation, obesity, homeostatic balance, and central sensitization, though the directional impact remains unclear (Elma et al., 2020). Evidence-based supplementation with whey protein, hydrolyzed collagen, creatine, and vitamin D may provide additional benefits when individualized (Escobar et al., 2026). The integration of nutrition with physiotherapy creates synergistic effects that enhance tissue repair, muscle protein synthesis, and overall rehabilitation outcomes (Sarkar et al., 2026).

Nutrition-Driven Regulation of Muscle Repair and Functional Adaptation

Nutrition plays a critical role in regulating muscle protein synthesis (MPS) and functional adaptation through multiple interconnected pathways. Leucine emerges as the most potent stimulator of the mechanistic target of rapamycin complex 1 (mTORC1) signaling pathway, increasing phosphorylation of mTORC1 substrates approximately 3-fold more than other essential amino acids (Ely et al., 2023). The convergence of leucine and IGF-1 signaling pathways demonstrates distinct mechanisms: IGF-1 activates mTORC1 through an AKT-TSC2 pathway, while leucine directly stimulates protein synthesis through alternative mTOR phosphorylation sites (Roberson et al., 2022). Essential amino acids, particularly leucine, drive transient increases in MPS following dietary protein consumption, with exercise enhancing skeletal muscle sensitivity to amino acids and extending the anabolic window up to 48 hours (Ely et al., 2023). Beyond leucine, other amino acids and metabolites like β-hydroxy-β-methylbutyrate and β-alanine contribute to skeletal muscle function regulation, energy expenditure, and performance enhancement (Kamei et al., 2020; Han, 2024).

Nutritional Influence on Bone Remodeling and Connective Tissue Healing

Nutritional factors play crucial roles in bone remodeling and connective tissue healing through multiple mechanisms. Loading combined with nutritional interventions such as vitamin C and gelatin improves tendon, ligament, and fascial structure and function by enhancing collagen synthesis (Steffen & Baar, 2020). Nutrition represents a safe, non-invasive strategy to positively influence each phase of fracture repair, though pre-existing nutritional deficiencies should be corrected for optimal healing outcomes (Roberts & Drissi, 2019). Dietary collagen, rich in glycine and proline, provides essential precursors required to facilitate connective tissue protein synthesis, as regular protein ingestion does not increase muscle connective tissue protein synthesis (Holwerda & van Loon, 2021). Specific nutrients target different wound healing phases: vitamin C enhances neutrophil migration and collagen synthesis, vitamin A promotes cytokine release and epithelial differentiation, zinc supports DNA and protein synthesis, while amino acids are crucial for wound scar stabilization (Palmieri et al., 2019).

Nutritional factors, particularly calcium and vitamin D, play crucial roles in bone remodeling and fracture healing. Vitamin D deficiency affects 57.5% of fracture patients, while hypocalcemia occurs in 35.0%, with deficient patients experiencing significantly delayed healing times (11.9 ± 2.5 weeks vs. 9.1 ± 1.7 weeks for sufficient levels). These deficiencies serve as independent predictors of delayed healing and reduced functional recovery scores (Khalil et al., 2026).

While pre-existing nutritional deficiencies should be corrected and nutritional status monitored during healing, evidence remains unclear whether supplementation beyond sufficiency provides additional benefits (Roberts & Drissi, 2019). A systematic review found controversial results for calcium/vitamin D supplementation in osteoporotic fracture healing, though other compounds showed positive effects (Chiavarini et al.,

2020). Calcium and vitamin D interact with parathyroid hormone and osteocalcin to regulate bone synthesis and resorption through various signaling pathways (Zastulka et al., 2024). Given the high prevalence of calcium and vitamin D deficiencies among individuals with musculoskeletal disorders, fortified functional foods may provide an effective approach to improving micronutrient intake. A recently developed calcium- and vitamin D3-fortified chocolate spread demonstrated excellent calcium retention, satisfactory vitamin D3 stability during storage, and favorable product characteristics, highlighting the feasibility of fortified food matrices as dietary vehicles for delivering nutrients that support bone remodeling and connective tissue healing (Zaidi & Randhawa, 2025).

Inflammation and Oxidative Stress: Nutritional Determinants of Recovery

Inflammation and oxidative stress are critical factors affecting nutritional recovery and patient outcomes. Elevated inflammatory biomarkers, particularly IL-6, predict increased mortality risk and reduced benefits from nutritional therapy in malnourished patients, with IL-6 showing stronger prognostic value than CRP or TNF-α (Wunderle et al., 2025). During critical illness, the balance between inflammation, oxidative stress, and immune response is crucial for recovery, as antioxidant capacity becomes compromised while micronutrient levels are depleted (Dresen et al., 2022). Phase angle, a bioelectrical impedance measure, correlates with inflammatory markers including CRP, TNF-α, and IL-6, serving as a potential indicator of cellular health and oxidative damage (Silva et al., 2022). Nutritional interventions can modulate these processes, with specific nutrients like β-carotene, vitamin C, vitamin D, and polyunsaturated fatty acids reducing inflammatory and oxidative stress markers, while Mediterranean dietary patterns demonstrate anti-inflammatory effects (Ding et al., 2020). Overall, these findings demonstrate that nutritional status, inflammatory and oxidative stress biomarkers, and biological recovery processes are closely interconnected. As shown in Figure 1, nutritional factors influence tissue repair through changes in key biomarkers, supporting physiological adaptation, improving the response to physiotherapy, and contributing to better functional recovery.

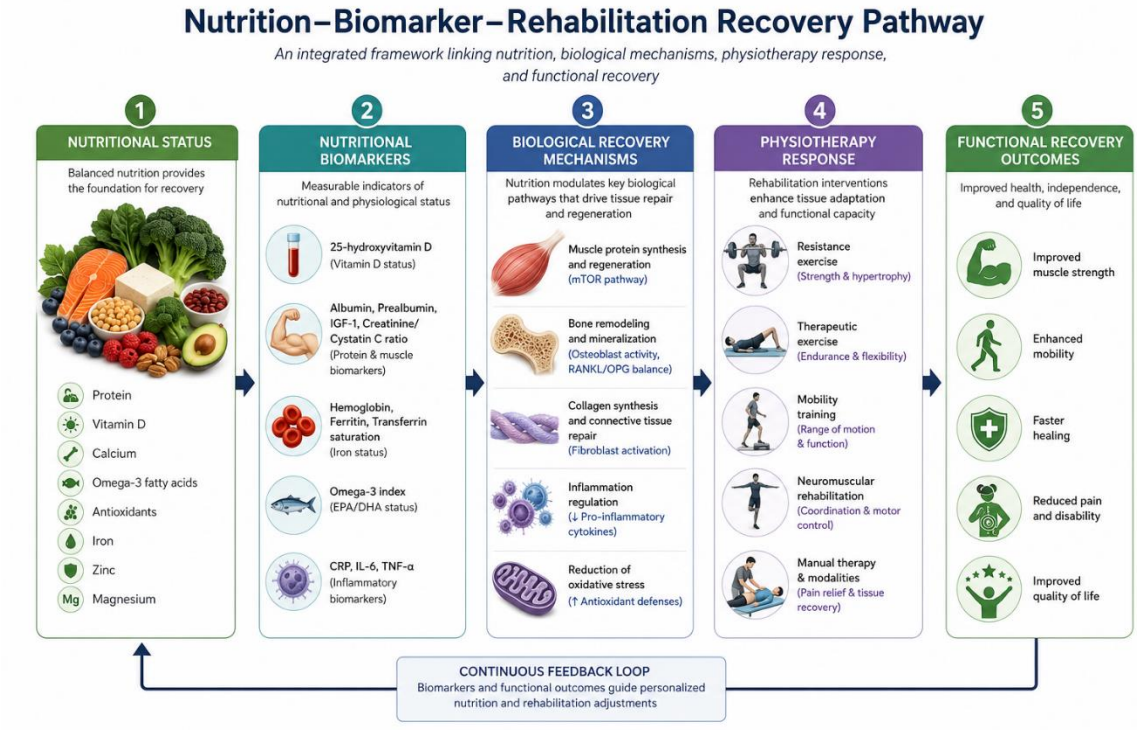

Figure 1. Nutrition–Biomarker–Rehabilitation Recovery Pathway.

Key Nutritional Biomarkers Associated with Rehabilitation Outcomes

Nutritional status emerges as a critical biomarker for rehabilitation outcomes across multiple patient populations. In stroke patients, high nutritional risk assessed through

tools like the Geriatric Nutritional Risk Index (GNRI), Prognostic Nutritional Index (PNI), and Controlling Nutritional Status (CONUT) score correlates with poor functional status and elevated inflammatory biomarkers including C-reactive protein, fibrinogen, and D-dimer (Di Vincenzo et al., 2023). Among older rehabilitation patients, malnutrition affects approximately 20.6% of admissions and significantly predicts slower functional gains, increased odds of functional decline (OR 3.95), and greater care requirements at discharge (Lambert et al., 2019). Meta-analysis evidence confirms that reduced nutritional status, particularly assessed via Mini Nutritional Assessment, associates with decreased functionality across geriatric rehabilitation populations, with sarcopenia prevalence reaching 40-76% (Wojzischke et al., 2020). While molecular biomarkers like inflammatory markers (TNF-α, IL-6) and neuroplasticity factors (BDNF, IGF-1) show promise for stroke rehabilitation prognosis, their clinical translation remains limited by methodological challenges (Ene et al., 2026).

Vitamin D Status: A Biomarker of Muscle Function and Recovery Potential

Vitamin D plays a crucial role in skeletal muscle metabolism through both genomic and non-genomic mechanisms, with vitamin D receptor (VDR) expression varying by age, sex, and pathology (Garcia et al., 2019). The hormone modulates muscle development, tissue repair, and regeneration by enhancing satellite cell function and myogenic factor expression (Iolascon et al., 2021). Vitamin D deficiency correlates with muscle metabolism disorders, including atrophy, sarcopenia, and cachexia, and results in myopathy characterized by fast-twitch fiber atrophy and fibrosis (Garcia et al., 2019; Iolascon et al., 2021).

However, evidence for vitamin D's role in post-exercise muscle recovery remains inconclusive. A systematic review found insufficient evidence that vitamin D supplementation improves post-exercise muscle recovery, possibly because anti-inflammatory effects occur faster than structural tissue recovery (Bello et al., 2021). While sufficient vitamin D levels correlate with improved muscle recovery and bone density, particularly benefiting athletes with known deficiency, robust randomized controlled trials are needed to establish evidence-based protocols (Kucharski et al., 2025).

Protein Status Biomarkers: Indicators of Muscle Recovery Capacity

Albumin and prealbumin have traditionally been used as nutritional status biomarkers, with prealbumin preferred due to its shorter half-life reflecting more rapid nutritional changes (Keller, 2019; Alnihier, 2021). However, recent evidence challenges their utility as nutrition markers. These visceral proteins are strongly influenced by inflammation rather than protein-energy stores, as inflammatory signals potently inhibit their synthesis (Keller, 2019; Evans et al., 2020). The current consensus indicates these proteins characterize inflammation rather than nutritional status, with hepatic reprioritization during illness resulting in lower concentrations (Evans et al., 2020).

Regarding muscle recovery capacity, albumin shows promise as a biomarker of muscle strength. In heart failure patients, serum albumin levels positively correlated with handgrip strength independent of dietary protein intake, while prealbumin showed no such correlation (Karanja et al., 2021). Despite limitations as nutritional markers, these proteins may serve as prognostic indicators for surgical outcomes and mortality in severe illness (Keller, 2019).

Research on protein status biomarkers for muscle recovery and sarcopenia assessment has identified several key indicators. The creatinine to cystatin C (Cr/CysC) ratio demonstrates moderate diagnostic accuracy and represents the most frequently utilized diagnostic biomarker for sarcopenia (Liu et al., 2025). The D3Cr dilution method, which assesses creatinine excretion as a biochemical measure of muscle mass, was suggested as more accurate than dual energy x-ray absorptiometry for measuring functional muscle mass (Rodríguez-Mañas et al., 2019).

Key biomarkers include inflammatory markers such as interleukin-6 (IL-6), C-reactive protein (CRP), and tumor necrosis factor-alpha (TNF-α), which are elevated in

sarcopenia patients (Liu et al., 2025; LeDrew et al., 2025). Additional important markers include insulin-like growth factor 1 (IGF-1), associated with skeletal muscle mass loss (Papadopoulou et al., 2022; LeDrew et al., 2025), and 3-Methylhistidine, a valuable biomarker for detecting increased muscle catabolism through urine excretion during muscle degradation (Papadopoulou et al., 2022).

Iron-Related Biomarkers: Linking Oxygen Availability with Rehabilitation Performance

Iron-related biomarkers play crucial roles in oxygen transport, energy metabolism, and rehabilitation outcomes. Hemoglobin, ferritin, and transferrin saturation are key diagnostic markers for iron disorders, with clinical applications in screening and monitoring programs (Semenova et al., 2024). Research demonstrates strong associations between these biomarkers and functional performance. Higher hemoglobin levels two days post-discharge were associated with better mobility scores two months after hip fracture surgery, while higher transferrin saturation correlated with improved mobility, walking speed, and functional test results (Aasbrenn et al., 2026). In cardiac rehabilitation, transferrin saturation emerged as a superior predictor of exercise capacity compared to ferritin, with low transferrin saturation predicting poor baseline exercise capacity in post-myocardial infarction patients (Zavrtanik et al., 2025). Similarly, in heart failure patients, transferrin saturation, rather than ferritin, was associated with better metabolic and hemodynamic exercise responses and improved clinical outcomes (Lee et al., 2025).

Omega-3 Fatty Acid Biomarkers: Modulating Inflammation and Recovery

Omega-3 fatty acids, particularly EPA and DHA, demonstrate significant potential as biomarkers for modulating inflammation and enhancing recovery in athletic populations. The Omega-3 Index, reflecting EPA and DHA proportions in red blood cell membranes, serves as a valuable biomarker for cardiovascular risk and may guide personalized supplementation protocols for athletes (Medoro et al., 2024; Palermi et al., 2025). Meta-analysis evidence shows that omega-3 supplementation significantly reduces inflammatory markers including interleukin-6, tumor necrosis factor-α, creatine kinase, and delayed-onset muscle soreness, with optimal effects achieved at doses ≥2g/day for minimum 6 weeks. The anti-inflammatory mechanisms involve nuclear factor-kappa B modulation and enhanced synthesis of specialized pro-resolving mediators (Li & Zhang, 2026). While studies suggest beneficial effects on endurance capacity, muscle soreness reduction, and immune modulation, the evidence base remains limited with diverse research designs, and effects may differ between elite athletes and recreational populations (Thielecke & Blannin, 2020).

Micronutrient Biomarkers Involved in Tissue Repair and Recovery

Micronutrients play essential roles in tissue repair and recovery through various mechanisms. Vitamin C is crucial for collagen synthesis and tissue regeneration, with supplementation showing improved healing outcomes, particularly in pressure ulcers (Bechara et al., 2022). During the proliferative phase of wound healing, vitamin C is specifically required for collagen formation and enhances neutrophil migration and lymphocyte activation during inflammation (Palmieri et al., 2019). Zinc participates in over 300 enzymatic reactions and is vital for DNA and protein synthesis, cell division, and immune function, making it indispensable for post-exercise recovery and wound healing (Kaczorowski et al., 2024; Palmieri et al., 2019). Magnesium, stored primarily in bones and muscles, is essential for protein synthesis, muscle relaxation, and energy metabolism, supporting athletic performance and recovery (Kaczorowski et al., 2024). These micronutrients work synergistically with other nutrients like vitamins A and E, selenium, and iron to support cell proliferation and new tissue formation (Stanescu et al., 2025).

Overall, nutritional biomarkers provide measurable indicators of nutritional status and the biological processes involved in musculoskeletal recovery. Figure 2 summarizes the

major nutritional biomarkers and their respective roles in tissue repair, regeneration, and rehabilitation.

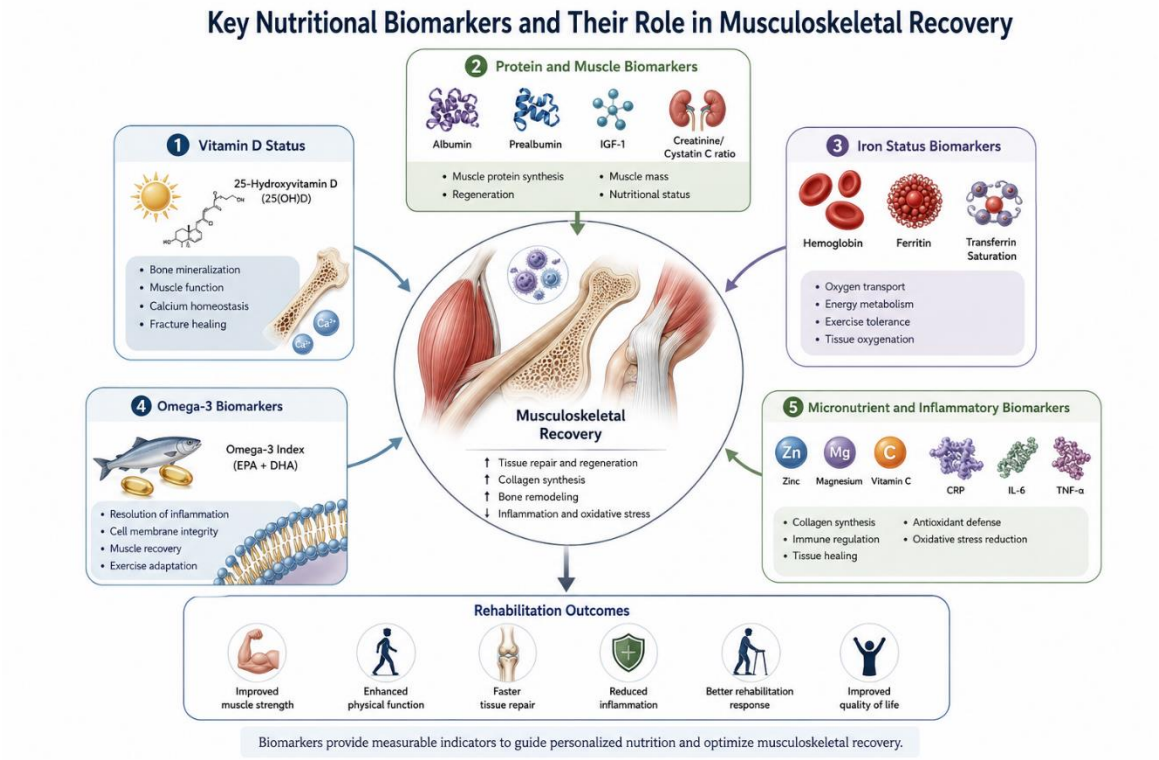

Figure 2. Key Nutritional Biomarkers and Their Role in Musculoskeletal Recovery.

Nutritional Biomarkers Across Different Musculoskeletal Rehabilitation Settings

Nutritional biomarkers play a crucial role across different musculoskeletal rehabilitation settings, with evidence demonstrating strong associations between nutritional status and rehabilitation outcomes. In geriatric rehabilitation populations, malnutrition prevalence ranges from 15-29%, with significant associations between reduced nutritional status and decreased functionality (Wojzischke et al., 2020; Conzade et al., 2019). The Mini Nutritional Assessment (MNA) serves as a key biomarker, with improvements in MNA scores correlating with enhanced physical performance measures like the Short Physical Performance Battery (Conzade et al., 2019). For athletic populations, nutritional strategies emphasizing balanced energy intake, high-protein and carbohydrate-rich diets support musculoskeletal injury rehabilitation, with promising supplementation options including collagen, creatine monohydrate, omega-3, and vitamin D (Giraldo-Vallejo et al., 2023). The integration of physiotherapy and nutrition creates synergistic effects that enhance tissue repair, inflammation control, and muscle protein synthesis across various musculoskeletal conditions (Sarkar et al., 2026). Sarcopenia prevalence remains high (40-76%) in geriatric rehabilitation settings, emphasizing the critical need for nutritional screening and targeted interventions (Wojzischke et al., 2020).

Osteoarthritis Rehabilitation: Predicting Functional Improvement Through Nutritional Status

Nutritional status significantly impacts osteoarthritis rehabilitation outcomes and functional improvement. Malnutrition affects approximately 20.6% of older rehabilitation patients and is associated with reduced functional, motor, and cognitive scores both on admission and discharge. Malnourished patients demonstrate slower rehabilitation gains and nearly four times greater odds of functional decline during treatment (Lambert et al., 2019). In geriatric rehabilitation populations, reduced nutritional status correlates with decreased functionality, with seven out of ten studies showing significant associations between poor nutrition and impaired function (Wojzischke et al., 2020).

Specific nutritional interventions show promise for osteoarthritis management. Maintaining adequate levels of vitamin D, along with vitamins A, B3, B9, B12, and iron, is associated with decreased pain and improved joint function (Martínez-García et al., 2025). Anti-inflammatory dietary approaches, including increased omega-3 fatty acids and reduced saturated fats, may effectively manage osteoarthritis by modulating immune responses and inflammatory pathways (Martínez-García et al., 2025; Dan et al., 2026).

Post-Fracture and Orthopedic Rehabilitation: Biomarkers of Bone Healing and Recovery

Vitamin D deficiency is highly prevalent in orthopedic patients, affecting 43-90% of individuals and significantly impacting fracture healing outcomes (Jha et al., 2025). Multiple studies demonstrate that adequate vitamin D levels accelerate fracture healing, with sufficient levels (>30 ng/mL) associated with healing times of 9.1-13.2 weeks compared to 11.9-16.4 weeks in deficient patients (Khalil et al., 2026; Kishore et al., 2024). Vitamin D deficiency was identified as an independent predictor of delayed healing and was associated with higher infection rates and increased nonunion risk (Jha et al., 2025).

Calcium deficiency, present in 35% of patients, also significantly delays healing, with normal calcium levels associated with shorter recovery times compared to hypocalcemia (Khalil et al., 2026). Sex differences exist in vitamin D metabolism during recovery, with men showing consistently lower 25-hydroxyvitamin D levels throughout the first year post-fracture (Cappola et al., 2025). Adequate vitamin D supplementation improves functional recovery and reduces subsequent fracture rates from 12.5% to 2.7% in osteoporotic patients (Kishore et al., 2024).

Sarcopenia and Age-Related Functional Decline

Sarcopenia, the age-related loss of muscle mass and strength, is associated with several key biomarkers that reflect underlying pathophysiological processes. Vitamin D deficiency consistently correlates with decreased muscle strength and increased sarcopenia prevalence, with supplementation showing benefits particularly in deficient individuals when combined with protein and resistance training (Fuentes-Barría et al., 2025). IGF-1 emerges as a promising biomarker, with reduced levels observed in sarcopenic adults compared to controls (Prokopidis et al., 2026). IGF-1 concentration, stimulated by food intake, is associated with skeletal muscle mass loss and plays a crucial role in sarcopenia progression (Papadopoulou et al., 2022). Additional muscle biomarkers including myostatin, interleukin-6, irisin, and procollagen type III N-terminal propeptide reflect processes of muscle anabolism, inflammation, metabolism, and remodeling (LeDrew et al., 2025). Growth differentiation factor-15 also shows elevation in sarcopenic individuals (Prokopidis et al., 2026). These biomarkers offer potential for early detection and personalized monitoring of muscle health decline.

Sports Injury Rehabilitation: Biomarkers Supporting Return to Activity

Biomarker-guided rehabilitation strategies are emerging as promising approaches for optimizing sports injury recovery and return-to-activity decisions. Current research demonstrates that various biomarkers can provide objective insights into physiological recovery processes. Muscle oxygen saturation (SmO2) serves as an important marker for internal physiological recovery of the quadriceps following ACL reconstruction (Prerana et al., 2024). For tendon injuries, proteomic approaches have identified biomarkers that are prognostic of good versus poor healing outcomes, potentially improving patient selection and treatment strategies (Hart et al., 2024). Traditional biomarkers like creatine kinase and interleukins assess muscle damage and inflammation but have limitations in specificity and sensitivity. Lipid mediators show promise for providing more precise insights into inflammatory processes following exercise, with distinct roles in pro-inflammatory, anti-inflammatory, and pro-resolving phases (Satija et al., 2025). These advances support personalized rehabilitation

interventions and enhanced recovery monitoring across diverse musculoskeletal conditions (Hart et al., 2023).

Integrating Nutritional Biomarkers into Clinical Rehabilitation Practice

Research demonstrates significant potential for integrating biomarkers into clinical rehabilitation practice to enhance personalized treatment approaches. Biomarker-guided rehabilitation strategies enable tailored interventions by providing objective insights into patients' physiological states and recovery potential, marking a shift toward precision medicine (Prerana et al., 2024). In stroke rehabilitation, multimodal biomarkers including neurofilament light chain, inflammatory markers, and neuroimaging parameters show promise for outcome prediction and individualized treatment planning (Nartea et al., 2025). Exercise therapy in breast cancer rehabilitation significantly affects metabolic biomarkers, glycemic and lipid profiles, and inflammatory markers including TNF-α, IL-6, and C-reactive protein (Invernizzi et al., 2022). Nutritional biomarkers play a crucial role in musculoskeletal rehabilitation, with optimized protein intake (2.0-3.0 g/kg/bm) and specific nutraceuticals like HMB, creatine, and omega-3 fatty acids supporting protein synthesis and tissue healing (Nikolova et al., 2026). Despite promising advances, challenges remain including assessment heterogeneity and technical complexity, requiring further research for clinical implementation.

From Nutritional Assessment to Personalized Rehabilitation Planning

Nutritional assessment and intervention play critical roles in rehabilitation outcomes across neurological and musculoskeletal conditions. Malnutrition in neurological disorders contributes to complications, delayed rehabilitation, and increased morbidity, making early nutritional screening and assessment essential for identifying at-risk patients and implementing appropriate interventions (Lee, 2022). The integration of physiotherapy and nutrition creates synergistic effects that enhance recovery, accelerate healing, improve muscle strength, and reduce rehabilitation duration in musculoskeletal disorders (Sarkar et al., 2026). Biomarker-guided rehabilitation strategies offer personalized interventions through objective insights into patients' physiological states, with inflammatory markers, neurophysiological indicators, and muscle oxygen saturation serving as key assessment tools (Prerana et al., 2024). In stroke rehabilitation specifically, early nutritional assessment and tailored dietary support demonstrate positive impacts on functional recovery, particularly in older and nutritionally vulnerable patients, with high nutritional risk correlating with poorer outcomes and increased inflammation (Kolanu et al., 2024).

Challenges in Biomarker-Based Rehabilitation Nutrition

Biomarker-guided rehabilitation nutrition faces several critical challenges that limit its clinical implementation. The lack of standardized biomarker panels represents a major obstacle, with significant heterogeneity in biomarker assessment protocols and inconsistent standardization across studies. Cost issues present substantial barriers, as the technical complexity and high implementation costs of biomarker assessments restrict widespread adoption (Prerana et al., 2024; Zhao et al., 2025). Limited clinical guidelines further complicate implementation, with regulatory ambiguity affecting the classification and clinical application of biomarker-guided interventions (Pokushalov et al., 2024). The critical need for longitudinal studies is evident, as most current research focuses on clinical populations with limited generalizability, and long-term studies remain scarce, raising questions about sustained efficacy and safety (Pokushalov et al., 2024; Zhao et al., 2025). Additionally, limited understanding of biomarker-outcome relationships and substantial barriers in clinical translation continue to hinder progress (Prerana et al., 2024; Zhao et al., 2025).

Future Perspectives and Research Directions

Biomarker-guided precision rehabilitation nutrition represents an emerging paradigm that leverages measurable biological indicators to personalize interventions and optimize patient outcomes. Current research demonstrates the potential of various

biomarker types, including inflammatory markers, neurophysiological indicators, and metabolic evaluations, to refine therapy plans and enhance recovery (Prerana et al., 2024). In stroke rehabilitation, molecular biomarkers like neurofilament light chain and circulating markers linked to oxidative stress and neuroprotection show promise for outcome prediction and individualized treatment strategies (Nartea et al., 2025).

Biomarker-driven approaches enable identification of nutritional deficiencies, metabolic imbalances, and disease predispositions, supporting targeted supplementation strategies (Pokushalov et al., 2024). Biomarkers of food intake measured in urine and blood offer objective dietary assessment tools that can adjust for compliance and misreporting, enabling more precise nutrition monitoring (Cuparencu et al., 2024). Despite promising advances, challenges remain including biomarker assessment heterogeneity, limited understanding of biomarker-outcome relationships, and the need for large-scale longitudinal studies to validate clinical applications.

Current neurorehabilitation research faces significant challenges requiring standardized approaches and large-scale studies to advance clinical implementation. Brain-computer interfaces show promise but need standardized protocols and clarification of neural mechanisms underlying motor recovery to justify widespread clinical adoption (Simon et al., 2021). The COVID rehabilitation field has established comprehensive research priorities emphasizing the need for safe rehabilitation approaches and examining implementation models across care continuums (O'Brien et al., 2024). Recent neurorehabilitation advances include multicenter randomized controlled trials testing novel interventions like personalized repetitive transcranial magnetic stimulation and deep brain stimulation protocols, demonstrating the field's movement toward rigorous clinical testing (Nakano et al., 2025). However, significant research gaps persist, particularly the lack of longitudinal studies, standardized outcome measures, and cost-benefit evaluations for rehabilitation interventions (Shen et al., 2025). Future priorities should focus on long-term effectiveness studies, standardized protocols, and scalable personalized care models to enhance evidence-based neurorehabilitation practices.

Conclusion

Nutritional status represents a critical but underutilized determinant of musculoskeletal rehabilitation outcomes. This review highlights that nutritional biomarkers provide valuable objective indicators of physiological readiness, recovery potential, and response to rehabilitation interventions. Biomarkers related to vitamin D, protein metabolism, iron status, omega-3 fatty acids, and micronutrients demonstrate potential for predicting muscle function, bone healing, inflammation control, and tissue regeneration across diverse musculoskeletal conditions. Integration of nutritional biomarker assessment with physiotherapy may facilitate a transition from generalized rehabilitation approaches toward precision-based, individualized care models. However, despite promising evidence, clinical application remains limited due to variability in biomarker selection, methodological inconsistencies, limited standardized protocols, and insufficient long-term validation studies. Future investigations should prioritize the development of validated biomarker panels, cost-effective assessment strategies, and longitudinal clinical trials to establish their predictive accuracy and therapeutic relevance. Combining nutritional assessment with functional, biochemical, and clinical parameters may enhance rehabilitation planning and improve patient outcomes. Ultimately, biomarker-guided nutritional strategies have the potential to strengthen the multidisciplinary management of musculoskeletal disorders by enabling targeted interventions, improving recovery monitoring, and supporting personalized rehabilitation pathways.

Declarations

Ethical Approval Certificate

Ethics committee approval is not required for this study.

Conflict of Interest

The author declares no conflict of interest.

Funding statement
No funding was received.

REFERENCES

Alnihier, M. M. H., Alotaibi, A. T., & Alanzi, A. S. B. (2021). Pediatric reference ranges for various laboratory markers as children's nutritional needs change. *Tennessee Research International of Social Sciences*, *3*(1), 17-28. DOI:10.53730/ijhs.v5ns1.14930

Aasbrenn, M., Jones, N. T., Svensson, C. K., Pedersen, M. W., Jensen, N. H., Pedersen, S., ... & Kristensen, M. T. (2026). Hemoglobin and transferrin saturation are associated with mobility and physical function two months after hip fracture surgery: an observational cohort study. *European Geriatric Medicine*, 1-8. DOI:10.1007/s41999-026-01407-z

Bello, H. J., Caballero-Garcia, A., Perez-Valdecantos, D., Roche, E., Noriega, D. C., & Cordova-Martinez, A. (2021). Effects of vitamin D in post-exercise muscle recovery. A systematic review and meta-analysis. *Nutrients*, *13*(11), 4013. https://doi.org/10.3390/nu13114013

Bechara, N., Flood, V. M., & Gunton, J. E. (2022). A systematic review on the role of vitamin C in tissue healing. *Antioxidants*, *11*(8), 1605. https://doi.org/10.3390/antiox11081605

CM, S., Patil, A. V., Prajapati, V., Sharma, R., & Thangavel, L. (2026). Effectiveness of physiotherapy-based rehabilitation in sports-related musculoskeletal injuries. *Bol Sustavy Pozvonochnik*, *16*(1), 12. doi. 10.22141/pjs.16.1.2026.491

Cranswick, I., Jones, A., Brogden, C., Mayhew, L., & Minshull, C. (2026). Rehabilitation remodelled: a narrative review of injury rehabilitation models and proposal of a multi-component MSK rehabilitation model. *Research in Sports Medicine*, *34*(2), 176-204. https://doi.org/10.1080/15438627.2025.2547191

Cashin, A. G., & Sterling, M. (2025). Optimising physical rehabilitation for people with musculoskeletal pain. *Pain*, *166*(11S), S131-S135. *DOI:* 10.1097/j.pain.0000000000003719

Chiavarini, M., Naldini, G., & Fabiani, R. (2020). The role of diet in osteoporotic fracture healing: a systematic review. *Current osteoporosis reports*, *18*(3), 138-147. DOI:10.1007/s11914-020-00573-8

Cappola, A. R., Abraham, D. S., Kroopnick, J. M., Huang, Y., Hochberg, M. C., Miller, R. R., ... & Magaziner, J. (2025). Sex-specific associations of vitamin D and bone biomarkers with bone density and physical function during recovery from hip fracture: the Baltimore Hip Studies. *Osteoporosis International*, *36*(5), 855-863. DOI:10.1007/s00198-025-07446-9

Cuparencu, C., Bulmuș-Tüccar, T., Stanstrup, J., La Barbera, G., Roager, H. M., & Dragsted, L. O. (2024). Towards nutrition with precision: unlocking biomarkers as dietary assessment tools. *Nature metabolism*, *6*(8), 1438-1453. DOI:10.1038/s42255-024-01067-y

Conzade, R., Phu, S., Vogrin, S., Bani Hassan, E., Sepúlveda-Loyola, W., Thorand, B., & Duque, G. (2019). Changes in nutritional status and musculoskeletal health in a geriatric post-fall care plan setting. *Nutrients*, *11*(7), 1551. https://doi.org/10.3390/nu11071551

Dan, J., Ding, H., Li, L., & Wu, Q. (2026). Immunonutritional biomarkers in osteoarthritis: mechanistic insights and prognostic potential. *Frontiers in Immunology*, *17*, 1769089. https://doi.org/10.3389/fimmu.2026.1769089

Dresen, E., Pimiento, J. M., Patel, J. J., Heyland, D. K., Rice, T. W., & Stoppe, C. (2023). Overview of oxidative stress and the role of micronutrients in critical illness. *Journal of Parenteral and Enteral Nutrition*, *47*, S38-S49.
https://doi.org/10.1002/jpen.2421Digital Object Identifier (DOI)

Ding, X. Y., Liu, K. Q., & Zhao, W. H. (2020). Effect of nutrition on human inflammatory and oxidative stress markers. *Zhonghua yi xue za zhi*, *100*(48), 3897-3902. DOI:10.3760/cma.j.cn112137-20200728-02230

da Silva[1], B. R., Orsso[1], C. E., Gonzalez[2], M. C., Sicchieri[3], J. M. F., Mialich[3], M. S., Jordao[3], A. A., & Prado, C. M. (2023). Phase angle and cellular health: inflammation and oxidative damage. *Reviews in Endocrine and Metabolic Disorders*, *24*(3), 543-562. DOI:10.1007/s11154-022-09775-0

Di Vincenzo, O., Pagano, E., Cervone, M., Natale, R., Morena, A., Esposito, A., ... & Scalfi, L. (2023). High nutritional risk is associated with poor functional status and prognostic biomarkers in stroke patients at admission to a rehabilitation unit. *Nutrients*, *15*(19), 4144. https://doi.org/10.3390/nu15194144

Detels, R., Karim, Q. A., Baum, F., Li, L., Leyland, A. H., Barrero, L. H., & Caban-Martinez, A. J. (2021). Musculoskeletal disorders. In *Oxford Textbook of Global Public Health*. Oxford University Press. https://doi.org/10.1093/med/9780198871682.003.0009

Escobar, E. A., Hernández, R. Y. E., Guzmán, J. M. V., & Sánchez, A. I. (2026). Estrategias nutricionales en la recuperación de lesiones musculoesqueléticas en deportistas: revisión narrativa. *Sapiens in Medicine Journal*, *4*(2), 1-16. DOI:10.71068/634dbp75

Elma, Ö., Yilmaz, S. T., Deliens, T., Clarys, P., Nijs, J., Coppieters, I., ... & Malfliet, A. (2020). Chronic musculoskeletal pain and nutrition: where are we and where are we heading?. *Pm&r*, *12*(12), 1268-1278. https://doi.org/10.1002/pmrj.12346Digital Object Identifier (DOI)

Ely, I. A., Phillips, B. E., Smith, K., Wilkinson, D. J., Piasecki, M., Breen, L., ... & Atherton, P. J. (2023). A focus on leucine in the nutritional regulation of human skeletal muscle metabolism in ageing, exercise and unloading states. *Clinical Nutrition*, *42*(10), 1849-1865. https://doi.org/10.1016/j.clnu.2023.08.010

Ene, B. G., Mitoiu, B. I., Ciornei, M. C., Coman-Stanemir, M., Voicu, A., Iliuta, F. P., & Papacocea, I. R. (2026). Seric Molecular Markers Correlated with Stroke Rehabilitation Outcomes: A Narrative Review. *Life*, *16*(1), 183. https://doi.org/10.3390/life16010183

Evans, D. C., Corkins, M. R., Malone, A., Miller, S., Mogensen, K. M., Guenter, P., ... & ASPEN Malnutrition Committee. (2021). The use of visceral proteins as nutrition markers: an ASPEN position paper. *Nutrition in Clinical Practice*, *36*(1), 22-28.
https://doi.org/10.1002/ncp.10588

Fuentes-Barría, H., Aguilera-Eguía, R., Angarita-Davila, L., Rojas-Gómez, D., Alarcón-Rivera, M., López-Soto, O., ... & Contreras-Velázquez, J. C. (2025). Vitamin D and sarcopenia: implications for muscle health. *Biomedicines*, *13*(8), 1863. https://doi.org/10.3390/biomedicines13081863

Gubajdullin, R.R., Kulakov, V.V., Yakovleva, A.V., Petrova, M.V., & Shestopalov, A.E. (2022). THE ROLE OF NUTRITIVE SUPPORT IN THE PHYSICAL AND FUNCTIONAL REHABILITATION OF CRITICAL PATIENTS: OVERVIEW. *Clinical nutrition and metabolism*. DOI:10.17816/clinutr96169

Garcia, M., Seelaender, M., Sotiropoulos, A., Coletti, D., & Lancha Jr, A. H. (2019). Vitamin D, muscle recovery, sarcopenia, cachexia, and muscle atrophy. *Nutrition*, *60*, 66-69. https://doi.org/10.1016/j.nut.2018.09.031

Giraldo-Vallejo, J. E., Cardona-Guzmán, M. Á., Rodríguez-Alcivar, E. J., Kočí, J., Petro, J. L., Kreider, R. B., ... & Bonilla, D. A. (2023). Nutritional strategies in the rehabilitation of musculoskeletal injuries in athletes: a systematic integrative review. *Nutrients*, *15*(4), 819. DOI:10.3390/nu15040819
https://doi.org/10.3390/nu15040819

Hutting, N., Caneiro, J. P., Ong'wen, O. M., Miciak, M., & Roberts, L. (2022). Patient-centered care in musculoskeletal practice: key elements to support clinicians to

focus on the person. *Musculoskeletal Science and Practice*, *57*, 102434. https://doi.org/10.1016/j.msksp.2021.102434

Han, J. (2024). The Regulatory Role of Nutrients in Muscle Protein Synthesis (MPS) and Muscle Protein Breakdown (MPB) with Resistance Exercise. *MedScien*. DOI:10.61173/0rmjvn25

Holwerda, A. M., & van Loon, L. J. (2022). The impact of collagen protein ingestion on musculoskeletal connective tissue remodeling: a narrative review. *Nutrition reviews*, *80*(6), 1497-1514. https://doi.org/10.1093/nutrit/nuab083

Hart, D. A., Ahmed, A. S., Chen, J., & Ackermann, P. W. (2024). Optimizing tendon repair and regeneration: how does the in vivo environment shape outcomes following rupture of a tendon such as the Achilles tendon?. *Frontiers in Bioengineering and Biotechnology*, *12*, 1357871. https://doi.org/10.3389/fbioe.2024.1357871

Hart, D. A., Ahmed, A. S., & Ackermann, P. (2023). Optimizing repair of tendon ruptures and chronic tendinopathies: Integrating the use of biomarkers with biological interventions to improve patient outcomes and clinical trial design. *Frontiers in Sports and Active living*, *4*, 1081129. https://doi.org/10.3389/fspor.2022.1081129

Iolascon, G., Moretti, A., Paoletta, M., Liguori, S., & Di Munno, O. (2021). Muscle regeneration and function in sports: a focus on vitamin D. *Medicina*, *57*(10), 1015. https://doi.org/10.3390/medicina57101015

Invernizzi, M., Lippi, L., Folli, A., Turco, A., Zattoni, L., Maconi, A., ... & Fusco, N. (2022). Integrating molecular biomarkers in breast cancer rehabilitation. What is the current evidence? A systematic review of randomized controlled trials. *Frontiers in Molecular Biosciences*, *9*, 930361. https://doi.org/10.3389/fmolb.2022.930361

Jha, G., Dhanjal, R., & Hamza, A. (2025). Vitamin D Supplementation in Orthopedic Trauma: Influence on Immune Modulation, Fracture Healing, and Infection Outcomes. *Cureus*, *17*(11). DOI: 10.7759/cureus.97842

Kamei, Y., Hatazawa, Y., Uchitomi, R., Yoshimura, R., & Miura, S. (2020). Regulation of skeletal muscle function by amino acids. *Nutrients*, *12*(1), 261. https://doi.org/10.3390/nu12010261

Khalil, M. H., Khan, M. A., Akram, M., & Khalil, M. H. (2026). Role of Serum Vitamin D and Calcium Levels in Fracture Healing and Functional Recovery: A Clinical Correlation Study: Vitamin D and Calcium in Fracture Healing and Recovery. *Developmental medico-life-sciences*, *3*(3), 19-24. https://doi.org/10.69750/dmls.03.03.0197

Kucharski, T., Brzyska, A., Kowalczyk, O., Prolejko, S., Gajęcki, B., Steć, G., ... & Maciejowski, M. (2025). The Role of Vitamin D3 in Musculoskeletal Recovery: Implications for Bone, Muscle, and Tendon Healing Across Athletic Disciplines. *Medical Science*, *29*(162). DOI:10.54905/disssi.v29i162.e134ms3622

Keller, U. (2019). Nutritional laboratory markers in malnutrition. *Journal of clinical medicine*, *8*(6), 775. https://doi.org/10.3390/jcm8060775

Karanja, P. W., Singla, A., Chery, J., Coston, A., & Vest, A. R. (2021). Serum Protein Levels as Biomarkers of Muscle Strength in Patients with End-Stage Systolic Heart Failure. *The Journal of Heart and Lung Transplantation*, *40*(4), S215. https://doi.org/10.1016/j.healun.2021.01.621

Kaczorowski, R., Forenc, T., Hunia, J., Górny, J., Janiszewski, M., Jurek, J., ... & Pelczarska, A. (2024). Magnesium and zinc as vital micronutrients enhancing athletic performance and recovery–a review. *Quality in Sport*, *33*, 56021-56021. DOI 10.12775/QS.2024.33.56021.

Kishore, D. R., Nandini, H., & Karri, N. (2024). Impact of Vitamin D Supplementation on Bone Healing Post-Fracture in Osteoporotic Patients. DOI:10.21276/ssr-iijls.2024.10.4.45

Kolanu, N. D., Ahmed, S., Kerimkulova, M. K., Stańczak, M., Vera, G. D. J. A., Shaikh, N., ... & Lima Sr, S. R. O. S. (2024). Influence of nutritional interventions on functional outcomes in stroke rehabilitation: a systematic review. *Cureus*, *16*(2). DOI: 10.7759/cureus.53711

Lambert, K., Taylor, E., Bowden, S., & Charlton, K. (2020). Nutritional status according to the Mini Nutritional Assessment predicts speed and degree of functional improvement and discharge outcomes in rehabilitation patients. *Journal of Nutrition in Gerontology and Geriatrics*, *39*(1), 16-29. https://doi.org/10.1080/21551197.2019.1689882

Liu, G., Jiang, S., Xie, W., Liu, X., Yang, G., Lu, W., ... & Li, Y. (2025). Biomarkers for sarcopenia, muscle mass, muscle strength, and physical performance: an umbrella review. *Journal of translational medicine*, *23*(1), 650. DOI:10.1186/s12967-025-06575-3

LeDrew, M., Sadri, P., Peil, A., & Farahnak, Z. (2025). Muscle Biomarkers as Molecular Signatures for Early Detection and Monitoring of Muscle Health in Aging. *Nutrients*, *17*(17), 2758. https://doi.org/10.3390/nu17172758

Lee, S., Houstis, N. E., Cunningham, T. F., Brooks, L. C., Chen, K., Slocum, C. L., ... & Malhotra, R. (2025). Transferrin saturation is a better predictor than ferritin of metabolic and hemodynamic exercise responses in HFpEF. *Heart Failure*, *13*(8), 102478. DOI:10.1016/j.jchf.2025.02.024

Li, Z., & Zhang, B. (2026). Effects of Omega-3 Supplementation on Inflammation and Recovery in Sports: A Meta-Analysis. *The FASEB Journal*, *40*(7), e71709. https://doi.org/10.1096/fj.202504783R

Lee, H. (2022). The importance of nutrition in neurological disorders and nutrition assessment methods. *Brain & Neurorehabilitation*, *15*(1), e1. DOI:10.12786/bn.2022.15.e1

Matkerimova, N., Akhmedov, K., & Dzhusupov, K. (2026). TRENDS IN THE PREVALENCE AND GLOBAL BURDEN OF MUSCULOSKELETAL DISEASES AMONG ADULTS: A NARRATIVE LITERATURE REVIEW OF THE PAST 10 YEARS. *Georgian medical news*, (372), 27-39.

Medoro, A., Buonsenso, A., Centorbi, M., Calcagno, G., Scapagnini, G., Fiorilli, G., & Davinelli, S. (2024). Omega-3 index as a sport biomarker: Implications for cardiovascular health, injury prevention, and athletic performance. *Journal of functional morphology and kinesiology*, *9*(2), 91. https://doi.org/10.3390/jfmk9020091

Martínez-García, R. M., Martínez, P. R., Jiménez-Ortega, A. I., & Lozano-Estevan, M. D. C. (2025). Nutritional guidelines for the improvement of patients with osteoarthritis. *Nutricion hospitalaria*, *42*(Spec No1), 68-71. DOI: 10.20960/nh.06096

Nikolova, M., Petkova, V., & Alakidi, A. (2026). The hidden potential of recovery: how nutrition and supplements change the rehabilitation process. *Pharmacia*, *73*, e186647. DOI:10.3897/pharmacia.73.e186647

Nguyen, A., Lee, P., Rodriguez, E. K., Chahal, K., Freedman, B. R., & Nazarian, A. (2025). Addressing the growing burden of musculoskeletal diseases in the ageing US population: challenges and innovations. *The lancet Healthy longevity*, *6*(5). DOI:10.1016/j.lanhl.2025.100707

Nartea, R., Savulescu, S., Potcovaru, C. G., & Poenaru, D. (2025). Toward Precision Post-Stroke Rehabilitation Medicine: Integrating Molecular, Imaging, and Computational Biomarkers for Functional Outcome Prediction. *Journal of Clinical Medicine*, *14*(22), 8077. https://doi.org/10.3390/jcm14228077

Nikolova, M., Petkova, V., & Alakidi, A. (2026). The hidden potential of recovery: how nutrition and supplements change the rehabilitation process. *Pharmacia*, *73*, e186647. DOI:10.3897/pharmacia.73.e186647

Nartea, R., Savulescu, S., Potcovaru, C. G., & Poenaru, D. (2025). Toward Precision Post-Stroke Rehabilitation Medicine: Integrating Molecular, Imaging, and Computational Biomarkers for Functional Outcome Prediction. *Journal of Clinical Medicine*, *14*(22), 8077. https://doi.org/10.3390/jcm14228077

Nakano, H., Matsugi, A., Ito, T., Oku, K., & Sakita, M. (2025). Exploring evidence for neurorehabilitation advancements. *Frontiers in Human Neuroscience*, *19*, 1636154. https://doi.org/10.3389/fnhum.2025.1636154

O'Brien, K. K., McDuff, K., Chattu, V. K., Churchill, K., Colantonio, A., Davenport, T. E., ... & Cameron, J. I. (2025). A framework of research priorities in COVID rehabilitation from the Rehabilitation Science Research Network for COVID: an international consultation involving qualitative and quantitative research. *Disability and Rehabilitation*, *47*(7), 1754-1763. https://doi.org/10.1080/09638288.2024.2382904

Picó, C., Serra, F., Rodríguez, A. M., Keijer, J., & Palou, A. (2019). Biomarkers of nutrition and health: new tools for new approaches. *Nutrients*, *11*(5), 1092. https://doi.org/10.3390/nu11051092

Prerana, C.S., Shilpashree, S., & Pal, S. (2024). BIO-MARKER GUIDED REHABILITATION STRATEGIES: A COMPREHENSIVE REVIEW. *PARIPEX INDIAN JOURNAL OF RESEARCH*. DOI:10.36106/paripex/6906592

Pokushalov, E., Ponomarenko, A., Shrainer, E., Kudlay, D., & Miller, R. (2024). Biomarker-guided dietary supplementation: a narrative review of precision in personalized nutrition. *Nutrients*, *16*(23), 4033. https://doi.org/10.3390/nu16234033

Prokopidis, K., Deane, C. S., Baoubbou, Z., & Beaudart, C. (2026). Circulating biomarkers in older adults with and without sarcopenia: a systematic review and meta-analysis. *The Journals of Gerontology, Series A: Biological Sciences and Medical Sciences*, *81*(7), glag140. https://doi.org/10.1093/gerona/glag140

Papadopoulou, S. K., Voulgaridou, G., Kondyli, F. S., Drakaki, M., Sianidou, K., Andrianopoulou, R., ... & Pritsa, A. (2022). Nutritional and nutrition-related biomarkers as prognostic factors of sarcopenia, and their role in disease progression. *Diseases*, *10*(3), 42. https://doi.org/10.3390/diseases10030042

Palmieri, B., Vadalà, M., & Laurino, C. (2019). Nutrition in wound healing: investigation of the molecular mechanisms, a narrative review. *Journal of Wound Care*, *28*(10), 683-693. https://doi.org/10.12968/jowc.2019.28.10.683

Palermi, S., Vecchiato, M., Brugin, E., Beltrami, G., & Casasco, M. (2024). The role of omega-3 fatty acids in sports nutrition: an overview. *Medicina dello Sport*, *77*(4), 471-479. DOI:10.23736/s0025-7826.25.04523-5

Roberts, J. L., & Drissi, H. (2020). Advances and promises of nutritional influences on natural bone repair. *Journal of Orthopaedic Research®*, *38*(4), 695-707. https://doi.org/10.1002/jor.24527

Roberson, P. A., Jefferson, L. S., & Kimball, S. R. (2022). Convergence of signaling pathways in mediating actions of leucine and IGF-1 on mTORC1 in L6 myoblasts. *American Journal of Physiology-Cell Physiology*, *323*(3), C804-C812. https://doi.org/10.1152/ajpcell.00183.2022

Rodriguez-Mañas, L., De Carvalho, I. A., Bhasin, S., Bischoff-Ferrari, H. A., Cesari, M., Evans, W., ... & Force, T. I. T. (2020). ICFSR task force perspective on biomarkers for sarcopenia and frailty. *The Journal of frailty & aging*, *9*(1), 4-8. https://doi.org/10.14283/jfa.2019.32

Steffen, D., & Baar, K. (2020). Effects of Loading and Nutrition on Fascia. In *Fascia, Function, and Medical Applications* (pp. 115-127). CRC Press.

Sivan, M., Phillips, M., Baguley, I., & Nott, M. (Eds.). (2019). *Oxford handbook of rehabilitation medicine*. Oxford University Press.

Sarkar, G.K., Sur, M., Bhuniya, O., Maity, S., & Tewari, S. (2026). The Synergistic Role of Physiotherapy and Nutrition in Musculoskeletal Rehabilitation: A Comprehensive Review. *International Journal for Research in Applied Science and Engineering Technology*. DOI:10.22214/ijraset.2026.83570

Semenova, Y., Bjørklund, G., Butnariu, M., & Peana, M. (2024). Iron-related biomarkers in the diagnosis and management of iron disorders. *Current Medicinal Chemistry*, *31*(27), 4233-4248. DOI:10.2174/0109298673263003231228060800

https://doi.org/10.2174/0109298673263003231228060800

Stanescu, C., Chiscop, I., Mihalache, D., Boev, M., Tamas, C., & Stoleriu, G. (2025). The roles of micronutrition and nutraceuticals in enhancing wound healing and tissue regeneration: A systematic review. *Molecules*, *30*(17), 3568. https://doi.org/10.3390/molecules30173568

Satija, S., Mitchell, T. W., Anthony, R., Peoples, G. E., & Sampson, J. A. (2026). From Strain to Repair: A Targeted Review of Lipid Mediators Driving the Inflammatory Cascade Following Exercise: S. Satija et al. *Sports Medicine*, *56*(1), 81-95. DOI:10.1007/s40279-025-02347-7

Simon, C., Bolton, D. A., Kennedy, N. C., Soekadar, S. R., & Ruddy, K. L. (2021). Challenges and opportunities for the future of brain-computer interface in neurorehabilitation. *Frontiers in neuroscience*, *15*, 699428. https://doi.org/10.3389/fnins.2021.699428

Shen, Y., Jiang, L., Lai, J., Hu, J., Liang, F., Zhang, X., & Ma, F. (2025). A comprehensive review of rehabilitation approaches for traumatic brain injury: efficacy and outcomes. *Frontiers in Neurology*, *16*, 1608645. https://doi.org/10.3389/fneur.2025.1608645

Thielecke, F., & Blannin, A. (2020). Omega-3 fatty acids for sport performance—are they equally beneficial for athletes and amateurs? A narrative review. *Nutrients*, *12*(12), 3712. https://doi.org/10.3390/nu12123712

Wunderle, C., Martin, E., Wittig, A., Tribolet, P., Lutz, T. A., Köster-Hegmann, C., ... & Schuetz, P. (2025). Comparison of the inflammatory biomarkers IL-6, TNF-α, and CRP to predict the effect of nutritional therapy on mortality in medical patients at risk of malnutrition: A secondary analysis of the randomized clinical trial EFFORT. *Journal of Inflammation*, *22*(1), 16. DOI:10.1186/s12950-025-00442-0

Wojzischke, J., van Wijngaarden, J., van den Berg, C., Cetinyurek-Yavuz, A., Diekmann, R., Luiking, Y., & Bauer, J. (2020). Nutritional status and functionality in geriatric rehabilitation patients: a systematic review and meta-analysis. *European Geriatric Medicine*, *11*(2), 195-207. DOI:10.1007/s41999-020-00294-2

Zastulka, A., Clichici, S., Culic, B., Pop, N. L., Olteanu, C. D., Delcea, C., ... & Mocan, T. (2024). 747 Calcium and vitamin D: roles, interactions and nutritional programming for bone development. *Balneo and PRM Research Journal*, *15*(4). https://bioclima.ro/Journal/index.php/BRJ/article/view/422

Zaidi, Z. F., & Randhawa, M. A. (2025). Calcium and Vitamin D3-Fortified Chocolate Spread: Development, Properties, and Stability. *RADS Journal of Food Biosciences*, *4*(2).

Zavrtanik, M., Jug, B. J., Mitja Lainscak, M. L., Bn, B. N., & Kambic, T. K. (2025). Iron deficiency and exercise capacity in patients after myocardial infarction attending cardiac rehabilitation program. *European Heart Journal*, *46*(Supplement_1), ehaf784-3915. https://doi.org/10.1093/eurheartj/ehaf784.3915

Zhao, Q., Zhang, C., Zhang, W., Zhang, S., Liu, Q., & Guo, Y. (2025). Applications and challenges of biomarker-based predictive models in proactive health management. *Frontiers in public health, 13*, 1633487. https://doi.org/10.3389/fpubh.2025.1633487