Microbiome modulation after injury to reduce muscle atrophy and accelerate return to play in adolescent basketball players: a randomized controlled trial

Modulación del microbioma tras una lesión para reducir la atrofia muscular y acelerar el regreso al juego en adolescentes jugadores de baloncesto: un ensayo controlado aleatorizador

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Abstract

DoriIntroduction: Musculoskeletal injuries in adolescent basketball athletes often lead to periods of immobilization, resulting in disuse muscle atrophy and delayed return-to-play (RTP). Emerging evidence suggests that the gut-muscle axis plays a key role in regulating muscle mass, systemic inflammation, and recovery.
Objective: This randomized controlled trial (RCT) investigated the efficacy of a targeted post-injury microbiome modulation intervention (probiotic and prebiotic supplementation) on mitigating muscle atrophy and accelerating RTP in adolescent basketball players.
Methodology: One hundred adolescent basketball athletes (aged 14–16 years) who sustained acute lower extremity injuries requiring at least two weeks of immobilization were randomized into an experimental group (n=50) receiving a daily multi-strain probiotic (including Lactobacillus plantarum and Akkermansia muciniphila) and prebiotic fiber, and a control group (n=50) receiving a placebo. Both groups underwent standard rehabilitation. Primary outcomes included changes in muscle mass (dual-energy X-ray absorptiometry), muscle strength (isokinetic dynamometry), and time to RTP. Secondary outcomes included systemic inflammatory markers (TNF-α, IL-6) and gut microbiome diversity (16S rRNA sequencing).
Results: The experimental group demonstrated significantly less muscle mass loss during the immobilization phase than the control group (2.1% vs. 4.8%, $p < 0.001$). Furthermore, the experimental group achieved RTP criteria significantly faster (38.5 vs. 46.2 days, $p < 0.001$). Systemic inflammatory markers were significantly lower in the experimental group, correlating with increased gut microbiome diversity and short-chain fatty acid (SCFA) production.
Discussion: The results were contrasted with the literature, confirming that targeted post-injury microbiome modulation is a highly effective adjunctive therapy.

Keywords

basketball injuries; gut-muscle axis; microbiome modulation; muscle atrophy; probiotics; return-to-play; sports rehabilitation.

Resumen

Introducción: Las lesiones musculoesqueléticas en los atletas adolescentes de baloncesto a menudo conllevan períodos de inmovilización, lo que resulta en atrofia muscular por desuso y retraso en el regreso al juego (RTP). La evidencia emergente sugiere que el eje intestino-músculo juega un papel clave en la regulación de la masa muscular, la inflamación sistémica y la recuperación.
Objetivo: Este ECA evaluó la eficacia de una intervención de modulación del microbioma (probióticos y prebióticos) para disminuir la atrofia muscular y acelerar el RTP en jugadores adolescentes.
Metodología: Se incluyeron 100 atletas adolescentes (14-16 años) con lesiones agudas de extremidades inferiores e inmovilización ≥2 semanas, aleatorizados a grupo experimental (probiótico multicepa diario: L. plantarum, A. muciniphila y fibra prebiótica) o control (placebo). Ambos recibieron rehabilitación estándar. Las variables principales fueron cambios en masa y fuerza muscular, y tiempo hasta RTP; las secundarias, marcadores inflamatorios (TNF-α, IL-6) y diversidad del microbioma (secuenciación 16S).
Resultados: El grupo experimental tuvo menor pérdida de masa muscular (2,1% vs 4,8%, p<0,001) y logró RTP más rápido (38,5 vs 46,2 días, p<0,001). También presentó menores marcadores inflamatorios, mayor diversidad microbiana y más ácidos grasos de cadena corta (AGCC).
Discusión: Los resultados se compararon con la literatura, confirmando que la modulación dirigida del microbioma tras una lesión es una terapia complementaria altamente eficaz..
Conclusión: La modulación del microbioma poslesión es una terapia adyuvante prometedora y no invasiva, que reduce la atrofia muscular y acelera el RTP en jóvenes atletas de baloncesto.

Palabras clave

atrofia muscular; eje intestino-músculo; lesiones en baloncesto; modulación del microbioma; probióticos; recuperación deportiva; regreso al juego.

Introduction

Among adolescent basketball players (aged 14–16), lower extremity injuries, particularly ankle sprains, knee ligamentous injuries, and skeletal muscle injuries (such as strains and contusions), are the most prevalent (Aksovic et al., 2024). Increasing the number of weekly sessions and training on different surfaces throughout the season has been associated with an increase in the number of injuries, especially in the ankle/foot and knee joints (Román et al., 2020). It is important to consider that the reparative behavior and rehabilitation approach for skeletal muscle injuries can be distinctive from ligamentous injuries, which consequently affects the progression of disuse atrophy (Giraldo-Vallejo et al., 2023). The standard of care for many of these acute injuries involves a period of immobilization or restricted weight-bearing to facilitate tissue healing. However, this necessary period of disuse inevitably leads to skeletal muscle atrophy, characterized by a rapid decline in muscle mass, cross-sectional area, and functional strength (Hardy et al., 2022).

Disuse muscle atrophy not only prolongs the rehabilitation process but also significantly delays the athlete's return-to-play (RTP) and increases the risk of re-injury upon return (Clanton et al., 2012). Rehabilitation programs for common sports injuries, including balance and strength training, have shown to be effective in facilitating the return to sports by improving functional recovery outcomes (Minozzi et al., 2020). The physiological mechanisms underlying disuse atrophy involve an imbalance between muscle protein synthesis (MPS) and muscle protein breakdown (MPB), driven by anabolic resistance, oxidative stress, and systemic inflammation (Howard et al., 2020). Traditional countermeasures have primarily focused on early mobilization, physical therapy, and nutritional interventions such as protein and leucine supplementation. While effective to a degree, these strategies commonly fail to completely abrogate muscle loss during the acute immobilization phase.

In recent years, researchers have found that the gut microbiome plays a key role in regulating how the body works, and its effects go well beyond the digestive system.

The concept of the "gut-muscle axis" proposes a bidirectional communication network between the intestinal microbiota and skeletal muscle (Przewłócka et al., 2020). The gut microbiome influences muscle mass and function through several mechanisms, including the production of short-chain fatty acids (SCFAs) such as butyrate and propionate, modulation of systemic inflammation, and regulation of amino acid bioavailability (Lahiri et al., 2019).

SCFAs, produced via the microbial fermentation of dietary fibers, have been shown to enhance skeletal muscle protein synthesis by activating the mTOR signaling pathway and increasing insulin sensitivity (Frampton et al., 2020). Furthermore, a healthy, diverse gut microbiome maintains intestinal barrier integrity. Following musculoskeletal trauma, systemic stress can induce intestinal permeability ("leaky gut"), allowing the translocation of lipopolysaccharides (LPS) into the systemic circulation (Roberts & Park, 2025). This endotoxemia triggers a systemic inflammatory response, elevating cytokines such as TNF-α and IL-6, which are potent stimulators of muscle protein breakdown via the NF-κB pathway (Tu & Li, 2023).

While the role of the microbiome in athletic performance is gaining traction, its application in injury recovery remains underexplored. Preclinical models have demonstrated that gut microbiota depletion exacerbates muscle atrophy, whereas administration of specific probiotic strains, such as Lactobacillus plantarum and Akkermansia muciniphila, can preserve muscle mass and improve strength during immobilization (Byeon et al., 2022; Chen et al., 2016). Additionally, proper nutritional strategies, including macronutrients and micronutrients, can accelerate the recovery process in sports, highlighting the need for an individualized nutritional approach for athletes (Bonilla et al., 2021). Despite these promising preclinical findings, there is a paucity of robust clinical trials evaluating the efficacy of microbiome modulation in injured athletes, particularly in adolescents. Adolescence represents a critical and unique window for microbiome intervention because the adolescent gut microbiota is still developing toward an adult-like profile and is highly responsive to external modulation (Carson et al., 2023). During this period of rapid somatic growth and hormonal changes, stabilizing the gut-muscle axis may yield more profound effects on muscle development and recovery than in mature adults.

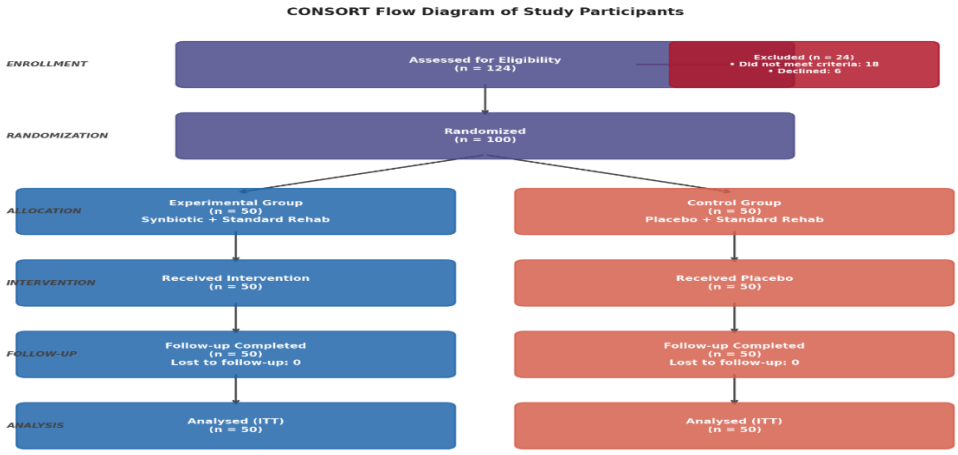
The primary objective of this randomized controlled trial (RCT) was to evaluate the efficacy of a targeted post-injury microbiome modulation intervention, comprising specific probiotic strains and prebiotic fibers, on reducing disuse muscle atrophy and accelerating RTP in adolescent basketball athletes (aged 14–16) recovering from lower extremity injuries.

Method

Study Design

The study used a double-blind, placebo-controlled, randomized clinical trial design and lasted for 12 months.

Figure 1: CONSORT Flow Diagram of Study Participants



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Participants

A total of 100 adolescent basketball athletes were recruited from a regional high school in Tirana. The inclusion criteria were: age between 14 and 16 years; active participation in competitive basketball (minimum of 3 sessions/week prior to injury); sustained an acute lower extremity injury (severe ankle sprain [Grade II-III], non-operative knee injury [ligamentous or muscular strain without complete rupture], or minor non-displaced fracture) requiring a prescribed immobilization or non-weight-bearing period of at least 14 days; and enrollment within 48 hours of the initial injury. All diagnoses were established by a specialist sports medicine physician and confirmed via imaging examination (MRI or X-ray) to accurately categorize the magnitude of the injury and residual edema, ensuring a standardized conservative approach.

The exclusion criteria included: injuries requiring surgical intervention; use of antibiotics, systemic corticosteroids, or commercial probiotic supplements within the 4 weeks prior to injury; history of chronic gastrointestinal diseases (Inflammatory Bowel Disease, Celiac disease); and known allergies to any components of the intervention or placebo. .

Procedure

Participants were randomly assigned in equal numbers to either the Experimental Group (n=50) or the Control Group (n=50) using a computer-generated sequence with block sizes of four. The allocation process was concealed with sequentially numbered, opaque, sealed envelopes. Neither the participants, their parents, nor the investigators who assessed outcomes knew which group participants were in. Supplements and placebos were given in identical opaque sachets. The intervention commenced within

48 hours of the injury and continued daily for 8 weeks, smoothly transitioning from the immobilization phase to the active rehabilitation phase.

In the experimental group, participants consumed a daily synbiotic sachet dissolved in water. The formulation contained: Lactobacillus plantarum TWK10 (1 × 10^10 CFU), Akkermansia muciniphila pasteurized strain (1 × 10^10 CFU), Bifidobacterium longum (1 × 10^10 CFU), and a prebiotic blend (5g of fructooligosaccharides and inulin). The control group received a daily placebo sachet, identical in taste, texture, and appearance to the active intervention, but containing maltodextrin. Both groups received standardized nutritional counseling to ensure adequate protein intake (1.6–2.0 g/kg/day) and caloric balance to support recovery. Both groups also underwent a standardized, progressive physical therapy protocol supervised by certified athletic trainers, progressing from immobilization to range-of-motion exercises, strengthening, and sport-specific functional drills.

Instrument

For both intervention and control groups, lean tissue mass of the injured lower extremity was assessed using Dual-Energy X-ray Absorptiometry (DEXA) at baseline (within 48 hours of injury), at the end of the immobilization phase (Day 14), and at the end of the intervention (Week 8). Isokinetic dynamometry (Biodex Medical Systems) was used to measure the moment of maximum force (peak torque) of the quadriceps and hamstrings (for knee injuries) or plantar/dorsiflexors (for ankle injuries) at 60°/s. Testing was performed once the athlete was cleared for maximal exertion (typically around Week 4-7) and at Week 8.

Time to Return-to-Play (RTP) was measured as the number of days from the date of injury to full, unrestricted clearance for competitive play. RTP clearance was determined by an independent sports medicine physician based on standardized criteria: absence of pain, full range of motion, >90% limb symmetry index (LSI) on functional hop tests, and successful completion of sport-specific tasks (Wellsandt et al., 2017; Simonsson et al., 2024). Furthermore, evaluating the psychological readiness for RTP is essential, as high psychological readiness and stress vulnerability can influence recurrence rates (Gómez-Espejo et al., 2022).

To assess systemic inflammation, fasting venous blood samples were collected at baseline, Day 14, and Week 8. Serum levels of Tumor Necrosis Factor-alpha (TNF-α) and Interleukin-6 (IL-6) were measured using enzyme-linked immunosorbent assay (ELISA) kits. Gut microbiome analysis used fecal samples collected at baseline and Week 8. Genomic DNA was extracted, and the V3-V4 region of the 16S rRNA gene was sequenced to study microbial alpha and beta diversity and the relative abundance of specific taxa. Fecal levels of short-chain fatty acids (SCFAs), such as acetate, propionate, and butyrate, were measured using gas chromatography-mass spectrometry (GC-MS).

Ethical Issues

The Ethical Committee of the Sports University of Albania approved the trial protocol (prot. no. 712/2, 09/04/2026), and the study adhered to the principles of the Declaration of Helsinki. Parents or legal guardians gave written informed consent for all participants, and adolescent athletes provided their informed assent.

Randomization and Blinding

Participants were randomly assigned in a 1:1 ratio to either the Experimental Group (n=50) or Control Group (n=50) using a computer-generated sequence with block sizes of four. Allocation was concealed with sequentially numbered, opaque, sealed envelopes. Both participants (and their parents) and investigators assessing outcomes were blinded to group assignments. Supplements and placebos were provided in identical opaque sachets.

Intervention

The intervention commenced within 48 hours of the injury and continued daily for 8 weeks, smoothly transitioning from the immobilization phase to the active rehabilitation phase.

Participants were assigned to either the experimental or control group for the duration. In the experimental group, participants consumed a daily synbiotic sachet dissolved in water. The formulation contained:

- Lactobacillus plantarum TWK10 (1 × 10^10 CFU)
- Akkermansia muciniphila pasteurized strain (1 × 10^10 CFU)
- Bifidobacterium longum (1 × 10^10 CFU)
- Prebiotic blend: 5g of fructooligosaccharides (FOS) and inulin.

Meanwhile, the control group received a daily placebo sachet, identical in taste, texture, and appearance to the active intervention, but containing maltodextrin.

Both groups received standardized nutritional counseling to ensure adequate protein intake (1.6–2.0 g/kg/day) and caloric balance to support recovery. Both groups also underwent a standardized, progressive physical therapy protocol supervised by certified athletic trainers, progressing from immobilization to range-of-motion exercises, strengthening, and sport-specific functional drills.

Outcome Measures

Primary Outcomes

1. **Muscle Mass**: For both intervention and control groups, lean tissue mass of the injured lower extremity was assessed using Dual-Energy X-ray Absorptiometry (DEXA) at baseline (within 48 hours of injury), at the end of the immobilization phase (Day 14), and at the end of the intervention (Week VIII).
2. Following the assessment of muscle mass, **isokinetic dynamometry** (Biodex Medical Systems) was used to measure the moment of maximum force (peak torque) of the quadriceps and hamstrings (for knee injuries) or plantar/dorsiflexors (for ankle injuries) at 60°/s. Testing was performed once the athlete was cleared for maximal exertion (typically around Week IV-VII) and at Week VIII.
3. **Time to Return-to-Play (RTP)**: The number of days from the date of injury to full, unrestricted clearance for competitive play. RTP clearance was determined by an independent sports medicine physician based on standardized criteria: absence of pain, full range of motion, >90% limb symmetry index (LSI) on functional hop tests, and successful completion (Wellsandt et al., 2017; Simonsson et al., 2024).

Secondary Outcomes

1. **Systemic Inflammation:** Fasting venous blood samples were collected at baseline, Day 14, and Week VIII. Serum concentrations of Tumor Necrosis Factor-alpha (TNF-α) and Interleukin-6 (IL-6) were quantified using enzyme-linked immunosorbent assay (ELISA) kits.
2. **Gut Microbiome Analysis:** Fecal samples were collected at baseline and Week 8. Genomic DNA was extracted, and the V3-V4 region of the 16S rRNA gene was sequenced to analyze microbial alpha and beta diversity, as well as the relative abundance of specific taxa.
3. **Short-Chain Fatty Acids (SCFAs):** Fecal concentrations of acetate, propionate, and butyrate were quantified using gas chromatography-mass spectrometry (GC-MS).

Data analysis

A sample size of 100 participants (50 per group) was calculated to provide 80% power to detect a 15% difference in time to RTP between groups, assuming an alpha level of 0.05. Data were analyzed using SPSS software (Version 28.0). Continuous variables were expressed as mean ± standard deviation (SD). Repeated measures Analysis of Variance (ANOVA) was used to assess changes in muscle mass, strength, and inflammatory markers over time between the two groups. Time to RTP was analyzed using Kaplan-Meier survival curves and the log-rank test. A p-value of <0.05 was considered statistically significant. An intention-to-treat (ITT) analysis was performed.

Results

Of the 124 athletes screened, 100 met the inclusion criteria and were randomized. All 100 participants completed the 8-week intervention and were included in the final analysis. There were no significant differences between the Experimental and Control groups at baseline regarding age, height, weight, body mass index (BMI), or injury type distribution (Table 1)

Table 1. Baseline Characteristics of Participants

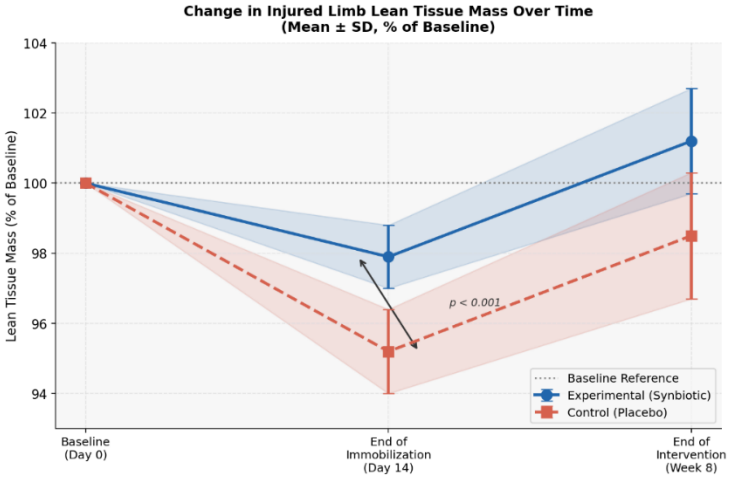
Characteristic	Experimental Group (n=50)	Control Group (n=50)	p-value
Age (years)	15.1 ± 0.8	15.2 ± 0.7	0.512
Gender (Male/Female)	28 / 22	26 / 24	0.687
Height (cm)	178.4 ± 8.2	177.9 ± 7.9	0.758
Weight (kg)	68.5 ± 6.4	69.1 ± 6.1	0.634
BMI (kg/m^2)	21.5 ± 1.8	21.8 ± 1.7	0.395
Injury Type			
- Severe Ankle Sprain	28 (56%)	29 (58%)	0.839
- Non-operative Knee	15 (30%)	14 (28%)	0.826
- Minor Fracture (Foot/Leg)	7 (14%)	7 (14%)	1.000

Primary Outcomes

Muscle Mass Preservation

During the initial 14-day immobilization, both groups lost lean tissue in the injured limb. The Experimental group had significantly less atrophy: on Day 14, they lost 2.1% ± 0.9% vs. 4.8% ± 1.2% in the Control group ($p < 0.001$). By Week VIII, the Experimental group's lean mass increased (+1.2% ± 1.5%) while the Control group remained below baseline (-1.5% ± 1.8%) (*$p < 0.01$*).

Figure 2**:** Change in Injured Limb Lean Tissue Mass Over Time



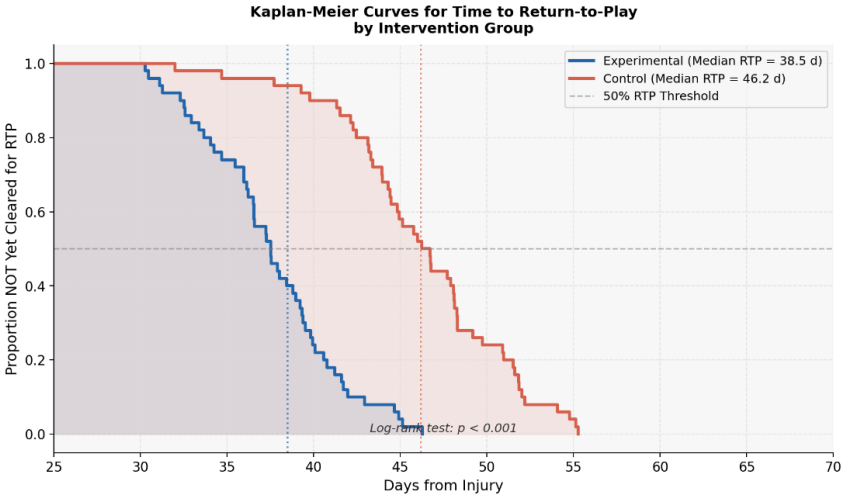
Muscle Strength Recovery

Isokinetic strength testing revealed that the Experimental group achieved higher peak torque values earlier in the rehabilitation process. At Week VIII, the Limb Symmetry Index (LSI) for peak torque was significantly higher in the Experimental group (92.4% ± 4.1%) compared to the Control group (85.6% ± 5.3%) (*$p < 0.001$*), indicating a more symmetrical and complete recovery of muscle strength.

Time to Return-to-Play (RTP)

The most clinically significant finding was the difference in time to RTP. The Experimental group achieved full medical clearance for unrestricted basketball participation significantly faster than the Control group. The mean time to RTP was 38.5 ± 4.2 days in the Experimental group, compared with 46.2 ± 5.8 days in the Control group (*$p < 0.001$*). Kaplan-Meier analysis confirmed a significantly accelerated RTP trajectory for the microbiome-modulated cohort.

Figure 3. Kaplan-Meier Curves for Time to Return-to-Play

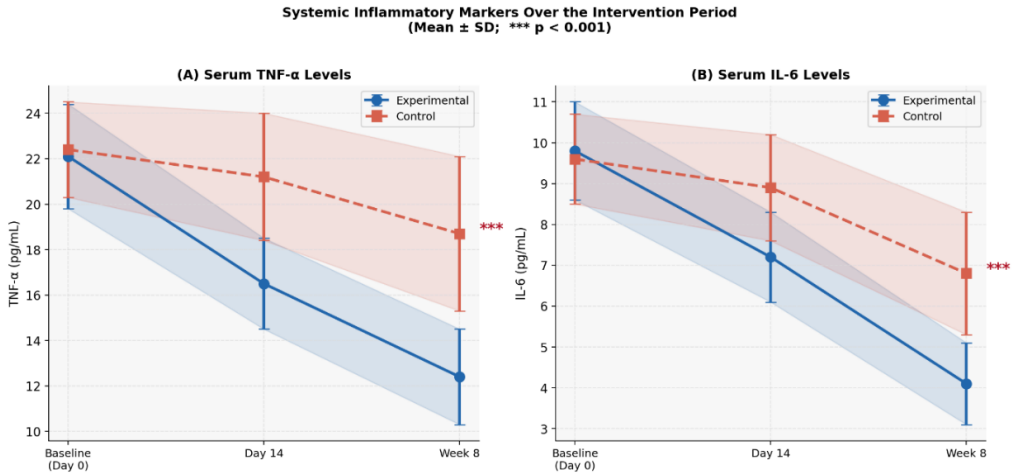


Secondary Outcomes

Systemic Inflammation

Baseline TNF-α and IL-6 levels were elevated in both groups due to acute trauma. By Day 14, the Experimental group showed a marked reduction in both markers compared with the Control group. At Week 8, TNF-α was 12.4 ± 2.1 pg/mL in the Experimental group, compared to 18.7 ± 3.4 pg/mL in Controls ($p < 0.001$). IL-6 was also lower: 4.1 ± 1.0 pg/mL versus 6.8 ± 1.5 pg/mL ($p < 0.001$).

Figure 4. Systemic Inflammatory Markers Over the Intervention Period

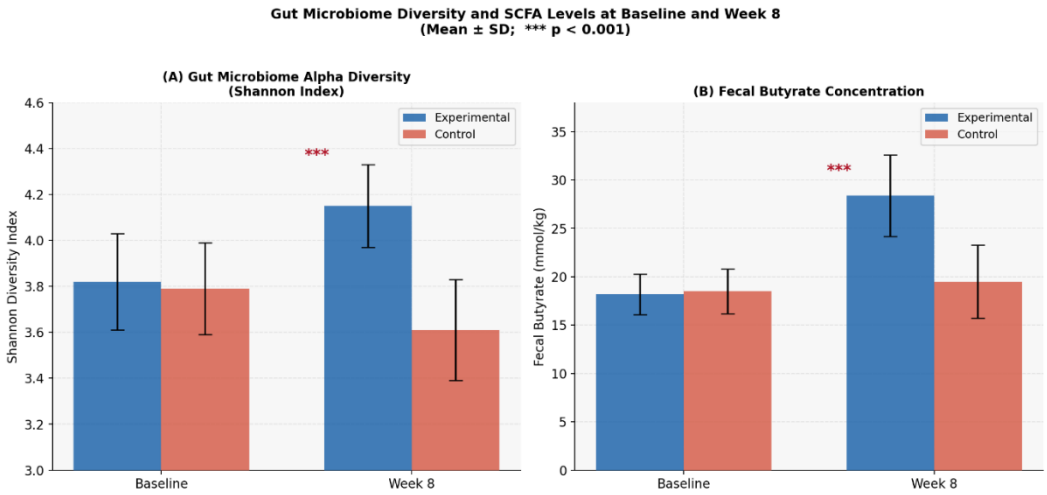


Gut Microbiome Diversity and SCFAs

16S rRNA sequencing revealed that, throughout the intervention period, the Experimental group maintained higher alpha diversity (Shannon index) than the Control group, which showed a transient decrease in diversity following injury and immobilization stress. Additionally, the Experimental group showed a significant increase in the relative abundance of the Lactobacillus, Bifidobacterium, and Akkermansia genera at Week 8 compared with the Control group.

Building on these findings, fecal SCFA analysis demonstrated that the Experimental group had significantly higher concentrations of total SCFAs, particularly butyrate (28.4 ± 4.2 mmol/kg vs. 19.5 ± 3.8 mmol/kg, $p < 0.001$) and propionate, at Week 8 compared to the Control group.

Figure 5: Gut Microbiome Diversity and SCFA Levels



Discussion

This randomized controlled trial offers compelling evidence that targeted post-injury microbiome modulation significantly attenuates disuse muscle atrophy and accelerates return-to-play in adolescent basketball athletes. To our knowledge, this is the first clinical trial to specifically investigate the gut-muscle axis as a therapeutic target during sports injury rehabilitation in an adolescent athletic population.

The immobilization period following a musculoskeletal injury is a critical window during which rapid muscle catabolism occurs. Our results show that supplementation with a specific synbiotic blend halved the rate of lean mass loss during the first 14 days of immobilization. Such preservation of muscle mass is likely mediated by the enhanced production of SCFAs, particularly butyrate, observed in the experimental group. Butyrate has been shown in preclinical models to activate the PI3K/Akt/mTOR pathway, thereby stimulating muscle protein synthesis, while simultaneously inhibiting the FoxO3a pathway, which drives protein degradation (Huang et al., 2019). By maintaining a more favorable anabolic-to-catabolic balance during disuse, the athletes in the experimental group had a greater baseline muscle mass upon entering the active rehabilitation phase.During this phase, emerging techniques such as blood flow restriction (BFR) training could also be considered to safely enhance muscle strength and hypertrophy in orthopedic rehabilitation, minimizing disuse atrophy with low-load exercise (Bahamondes-Avila et al., 2024.).

The goal of sports rehabilitation is a safe and rapid return to competition. The experimental group met the RTP criteria nearly 8 days earlier than the control group. This accelerated timeline is multifactorial. First, the preservation of muscle mass during immobilization meant that less time was required to rebuild lost tissue during active physical therapy. Second, the superior recovery of muscle strength, as evidenced by the higher Limb Symmetry Index at Week 8, allowed athletes to progress through functional and sport-specific drills (cutting, jumping) more rapidly and safely. In basketball, where explosive lower-body power is critical, restoring symmetrical strength is a prerequisite for RTP and injury prevention (Taberner et al., 2023; Wellsandt et al., 2017; Simonsson et al., 2024). Moreover, integrating targeted physical training, such as weight-free circuit training, can further improve explosive power in elite basketball players, complementing nutritional interventions (Kurti et al., 2026). Additionally, studies show that unilateral strength training can significantly improve hamstring asymmetry and jumping performance in sub-elite athletes (Wiriawan et al., 2024).

Acute injury triggers a necessary localized inflammatory response; however, prolonged or systemic inflammation exacerbates muscle wasting and delays tissue healing (Stratos et al., 2022) Intense physical activity and stress are known to elevate TNF-α and other inflammatory markers in athletes, necessitating targeted recovery strategies (Devi et al., 2023). The trauma and subsequent stress of injury can compromise the intestinal barrier, allowing harmful substances from the gut to enter the bloodstream (a process known as endotoxemia) and causing increased levels of signaling molecules

called cytokines throughout the body. Our data demonstrates that microbiome intervention effectively blunted the systemic inflammatory response, as evidenced by significantly lower levels of TNF-α and IL-6, key inflammatory cytokines. Akkermansia muciniphila and Lactobacillus plantarum help enhance proteins that form tight junctions between intestinal cells, thereby reducing gut permeability and preventing the escape of pro-inflammatory molecules, such as lipopolysaccharides (LPS), from gut bacteria into the circulation (Kang et al., 2024). This anti-inflammatory effect likely created a more favorable systemic environment supporting muscle repair and regeneration. These findings are consistent with recent research showing that anti-inflammatory supplementation, such as Omega-3, can significantly reduce serum TNF-α levels, decrease pain intensity, and maintain muscle strength following high-intensity training (Ayubi et al.,2022; Bafirman et al., 2024). Furthermore, the administration of curcumin has been found to increase IL-10 levels, an anti-inflammatory cytokine that helps control uncontrolled inflammation after high-intensity exercise (Ayubi & Sari., 2023). Other recovery modalities, such as cold water immersion, have also proven highly effective in mitigating inflammation, significantly reducing IL-6, malondialdehyde (MDA), and creatine kinase (CK) levels in both adolescent males and female soccer players post-exercise (Dewangga et al., 2025; Pranoto et al., 2025).

Adolescent athletes represent a unique population. They are undergoing rapid somatic growth, and their baseline metabolic and hormonal profiles differ from those of adults. The disruption of training and the physiological stress of injury might have considerable impacts on their development. The finding that a non-invasive, safe nutritional intervention can significantly improve healing trajectories is highly clinically relevant. It offers sports medicine practitioners an adjunctive tool to standard physical therapy and macronutrient optimization. The implementation of structured strength training programs in physical education and youth sports has been shown to effectively enhance both upper and lower limb strength in adolescents, providing a solid foundation for injury prevention and recovery (Martins et al., 2020).

Outside the direct scope of adolescent basketball, the principles of microbiome modulation demonstrated in this study have extensive implications for sports medicine and orthopedic rehabilitation. The ability to attenuate disuse atrophy via the gut-muscle axis suggests that synbiotic supplements could become a standard prophylactic measure for any athlete facing forced immobilization, regardless of the sport. Recent evidence confirms that the gut-muscle axis is a critical bidirectional signaling network, where targeted microbial modulation, such as synbiotic supplementation, can significantly reduce key markers of exercise-induced muscle damage and inflammation, thereby enhancing recovery (Carlone & Parisi, 2025; Xu & He, 2025; Bideshki et al., 2026). Furthermore, mitigating leaky gut syndrome is increasingly recognized as vital for modulating systemic endotoxemia, which indirectly reduces local musculoskeletal inflammation and nociceptive pain during rehabilitation (Álvarez-Herms et al., 2023). For sports nutritionists and dietitians, these findings underscore the need to move beyond traditional macronutrient paradigms and adopt focused approaches that cultivate a resilient, diverse gut microbiome. This aligns with systematic reviews highlighting the potential of various herbal and nutritional supplements to accelerate recovery from exercise-induced muscle damage by modulating inflammatory biomarkers (Anugrah et al., 2024).

While the results are robust, several limitations need to be acknowledged. First, although explosive strength is a critical descriptor for verifying sports return in basketball, it was not directly measured during the RCT protocol due to logistical constraints at the clinical sites. Instead, isokinetic dynamometry was used as a proxy for functional strength recovery. Second, the study focused on a specific age group (14-16 years) and a specific sport (basketball). Therefore, the findings may not be entirely generalized to adult professionals or athletes in endurance sports. Third, while we measured systemic inflammatory markers and fecal SCFAs, we did not perform muscle biopsies to directly quantify intramuscular signaling pathways due to the obtrusive nature of the procedure in a pediatric population. Future research must explore the dose-response relationship of specific probiotic strains, and critically, include a longitudinal follow-up period to verify the possibility of exacerbation of the initial lesion and to assess the long-term effects of the intervention on re-injury rates after sports reintegration.

Conclusions

In conclusion, this randomized controlled trial demonstrates that post-injury microbiome modulation with a targeted symbiotic formulation is a highly effective adjunctive therapy for adolescent basketball athletes.

By retaining muscle mass during immobilization, dampening systemic inflammation, and accelerating muscle strength recovery, this intervention significantly shortens the timeline to a safe return to play. Integrating gut microbiome health into sports rehabilitation protocols represents a paradigm shift in orthopedics and sports medicine, offering a novel approach to optimize recovery and performance in young athletes.

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