

**Case Report**
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## Neuromuscular Training Protocols: Tailoring Strategies for Improved Functional Outcomes and Second ACL Injury Prevention

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### ABSTRACT

An ACL sprain or tear is one of the most prevalent knee ailments. Because of the significant degree of variation in their presentation and consequences, treatment must be tailored to patient demographics, the severity of the damage, and the patient's long-term improvement profile. This white paper delves into the critical role of neuromuscular training in post-operative ACL reconstruction patients, focusing on tailoring protocols to enhance functional outcomes and reduce the risk of second ACL injuries. Through an extensive review of the literature and evidence-based analysis, this paper aims to provide insights into the optimal design and implementation of neuromuscular training strategies.

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**Received:** August 02, 2022; **Accepted:** August 09, 2022; **Published:** August 16, 2022

**Keywords:** Anterior Cruciate Ligament, Neuromuscular Training, Effectiveness, Rehabilitation

### Introduction

#### A. Brief Overview of ACL Injuries

The ACL is the most often injured knee ligament. An ACL sprain or tear is one of the most prevalent knee ailments. Injury typically happens during activity/sports play, which involves fast changes in direction of movement, rapid stopping, odd jumping and landing, a direct blow to the lateral aspect of the knee, or slowing down while sprinting. Most ACL injuries occur in combination with injury to other knee structures such as articular cartilage, meniscus, or other ligaments [1]. ACL injuries can be described as direct contact, indirect contact, or non-contact, with non-contact injuries being the most prevalent and caused by forces created within the athlete's body [2]. Knee joint problems and injuries are on the rise as the number of injuries in everyday life, such as road traffic accidents (RTAs) and industrial accidents, increases [3]. Ligamentous injuries are the most prevalent type of knee injury, with the Anterior Cruciate Ligament (ACL) being the most commonly injured, especially when the knees are in a valgus alignment [4]. ACL injuries involve other ligaments, including the medial collateral ligament and the menisci, and compression during valgus movement is always on the lateral side [5].

In the United States alone, the prevalence of ACL injuries has been estimated to be 1 in 3500 every year, with females being at a higher risk, and 300,000 ACL reconstructive procedures conducted each year [4, 6].

#### B. Purpose of Neuromuscular Study

Therapeutic activities are an essential part of physical therapy. Therapeutic activities should be started as soon as possible in

the treatment process, and all patients must complete exercise regimens as tasks [9].

Neuromuscular training seeks to enhance the patient's body to a state even better than before their injury, not just to recover the functioning of affected joints. Improved movement patterns, coordination, muscle strength, endurance, and agility are thus beneficial in reducing recurrence and future injuries [10].

After an injury, neuromuscular control plays a crucial role in restoring and improving joint function and body condition. To prevent additional injury and recurrence, long-term measures such as movement patterns, coordination, muscle strength, endurance, and agility should be prioritized [7].

To initiate a movement, neuromuscular control is required, and the neurological and muscular systems collaborate to achieve this goal. This control is critical to the efficacy of a movement. Some rehabilitation activities are designed to strengthen the neuromuscular components of movement. It is an important part of ACL rehab training because it is involved in ACL injuries. Understanding the biomechanics of how to stand after jumping is essential and knowing all preventive actions can help to lower this danger. Plyometric exercise, balance training, and rehabilitative training are all part of this training regimen. NMT's protective role has also been proven in the literature [8].

### Literature Review

A. **Dubljanin Raspopovic E, Matanovic D, Kadija M** [13]

In this study, a purpose-made receiver was used to measure voltage variations during passive knee flexion-extension and anterior tibial translation maneuvers. The variables evaluated included first peak latency, normalized amplitude, and slope of voltage over time.

Notably, the system detected significant changes in the slope of the voltage/time signal, with higher specificity and sensitivity observed during anterior tibial translation (ATT) after experimental anterior cruciate ligament (ACL) section. The findings suggest that enhanced pattern recognition learning from these structures could be a future target for proprioceptive training after ACL injury.

**B. Bonsfills N, Raygoza JJ, Boemo E, Garrido J, Nuñez A, Gómez Barrera E [14]**

This study investigated the proprioceptive capabilities of ACL-reconstructed knee joints after surgery. The findings revealed those 6 weeks post-surgery, the proprioceptive abilities were significantly reduced. However, a special proprioceptive rehabilitation program conducted over six weeks effectively mitigated this deficit. Notably, in the patient group, the sensorimotor function of both knee joints improved to a level surpassing that of the control group. Additionally, the static balance index was better in the operated extremity.

**C. Webster KE, Feller JA, Klemm HJ [15]**

Researchers assessed the impact of delaying return to competitive sport after primary ACL reconstruction. The study included 142 eligible patients who underwent their first primary ACL reconstruction. These patients were informed about the risk of further injury and advised not to return to sport before 12 months postoperatively. A separate comparison group of 299 patients underwent ACL reconstruction without specific return-to-sport delay advice. The study followed up with patients for 3 to 5 years and determined return-to-sport status and subsequent ACL injuries (graft rupture or contralateral injury). The findings revealed that even patients who delayed return until 12 months had a high subsequent ACL injury rate. Further research is needed to identify strategies to reduce reinjury rates in younger athletes.

**D. Mandelbaum BR, Silvers HJ, Watanabe DS, Knarr JF, Thomas SD, Griffin LY, Kirkendall DT, Garrett W Jr [16]**

In this study, researchers investigated the effectiveness of a neuromuscular and proprioceptive training program in preventing noncontact anterior cruciate ligament (ACL) injuries in female athletes. The study involved female soccer players between the ages of 14 and 18. The enrolled subjects in the intervention group experienced an 88% decrease in ACL injuries compared to the control group in the 2000 Season. In the second year (2001 Season), there was a 74% reduction in ACL tears in the intervention group compared to the age- and skill-matched controls. These findings highlight the importance of incorporating sports-specific training to enhance ACL injury prevention in female soccer players.

**E. Caraffa A, Cerulli G, Proietti M, Aisa G, Rizzo A [17]**

In a prospective controlled study involving 600 soccer players across 40 semiprofessional or amateur teams, the impact of proprioceptive training was investigated. The proprioceptively trained group exhibited a remarkable reduction in ACL injuries, with an incidence of 1.15 injuries per team per year. In contrast, the control group (300 players) received no special balance training and experienced significantly fewer ACL injuries ( $P < 0.001$ ). Proprioceptive training emerged as a valuable strategy for preventing ACL injuries in soccer players.

**F. Cerulli G, Benoit DL, Caraffa A, Ponteggia F [18]**

Cerulli, Benoit, Caraffa, and Ponteggia developed a program aimed at reducing the incidence of ACL injuries in soccer players. The program focused on proprioceptive control mechanisms at the knee joint. Soccer players trained with this program experienced significantly fewer ACL injuries compared to those without

specialized training ( $P < 0.001$ ). Proprioceptive training, integrated into soccer training regimens, emerges as a valuable preventive measure against ACL injuries.

**G. Risberg MA, Beynon BD, Peura GD, Uh BS. [19]**

The study involved twenty subjects who experienced acute ACL disruption and underwent reconstruction with a bone-patellar tendon-bone graft. Proprioception in the ACL-reconstructed knee did not significantly differ from the contralateral uninvolved knee one year or more after surgery. Functional knee bracing did not appear to improve proprioception in patients who underwent ACL reconstruction and were followed up for an average of two years after surgery.

**H. Fremerey RW, Lobenhoffer P, Zeichen J, Skutek M, Bosch U, Tschernhe H [20]**

This study investigated the effect of anterior cruciate ligament (ACL) reconstruction on knee proprioception in healthy volunteers and patients with acute and chronic anterior instability. ACL reconstruction partially restores impaired proprioception, with gradual improvement over time. However, complete restoration, particularly in the mid-range, may take several years. Rehabilitation programs should focus on targeted exercises to address proprioceptive deficits and improve joint stability.

**Tailoring Neuromuscular Protocol**

As we know, ACL rehabilitation can be divided into the following phase

- **Phase 1: Maximum Protection Phase**
  - Day 1 to Week 4
- **Phase 2: Moderate Protection Phase**
  - Week 5 – 10
- **Phase 3: Minimum Protection Phase**
  - Week 11 – 24
- **Phase 4: Return To Activity Phase**
  - 6 months+

**A. Goals**

- 1) To improve proprioception, balance, and stability with standing on unstable surfaces and walking activities on uneven surfaces.
- 2) Gradually increase walking distance and speed.
- 3) Progressively incorporating demanding functional activities like stair climbing, jogging, and agility drills.
- 4) Plyometrics, jumping, hopping.
- 5) Regain cardiorespiratory fitness with aerobic conditioning activities.

**B. Inclusion**

- 18 – 40 years
- Within 6 weeks post ACL reconstruction operation
- Patients who were previously engaged in sports or physically demanding activities before injury.
- Patients who have received medical clearance to participate in the neuromuscular training program.

**C. Exclusion**

Any other significant lower extremity or medical condition that can impact the study

- Unable to commit to the study.
- Patients with multiple ligament injuries.
- Patients with pre-existing orthopaedic conditions affecting the knee joint.
- Pregnant individuals, due to potential impacts on training participation.

- Patients who are unable to understand the instructions for neuromuscular training due to language barriers or cognitive impairment.
- Patients with inadequate follow-up data or loss of follow-up during the study period.

#### **D. Conventional Physiotherapy Protocol**

##### **1) Goals**

- Primarily focuses on restoring basic range of motion, reducing pain and swelling, and regaining general muscle strength.
- Progresses through stages of passive range of motion, active range of motion, and strength exercises.

##### **2) Exercises:**

- Basic range of motion exercises (ankle pumps, heel slides).
- Passive and active-assisted knee range of motion exercises.
- Quadriceps sets and hamstring isometrics.
- Initial weight-bearing and gait training.
- Limited emphasis on neuromuscular control, proprioception, and sport-specific movements.

#### **E. Structured Neuromuscular Training Program**

##### **Phase 1: Early Post-Operative Phase (Weeks 0-2)**

###### **Goals**

- Minimize swelling and pain.
- Restore basic mobility.
- Begin early neuromuscular activation.
- Educate the patient on movement precautions.

###### **Exercises**

- 1) Ankle Pumps: To improve circulation and reduce swelling. Perform 2-3 sets of 15-20 reps, several times a day.
- 2) Quadriceps Sets: Isometric contractions of the quadriceps muscles. Hold for 5 seconds, 2-3 sets of 10-15 reps, several times a day.
- 3) Passive Knee Range of Motion (ROM): Gentle knee flexion and extension exercises within the pain-free range as directed by the surgeon.

##### **Phase 2: Intermediate Phase (Weeks 2-6)**

###### **Goals**

- Restore full knee range of motion.
- Begin weight-bearing as tolerated.
- Enhance neuromuscular control and proprioception.

###### **Exercises**

- 1) Active Assisted Knee Flexion: Use a towel or a belt to gently assist in knee flexion stretches. Hold for 15-30 seconds, 2-3 sets, 2-3 times a day.
- 2) Mini-Squats: Partial squats with support (e.g., holding onto a stable surface). Focus on proper form and control. 2-3 sets of 10-15 reps.
- 3) Static Balance Drills: Stand on one leg with eyes open, then eyes closed. Progress by adding head movements and holding for longer durations.
- 4) Bridging Exercises: Lie on your back and lift your hips off the ground. 2-3 sets of 10-15 reps.

##### **Phase 3: Strengthening Phase (Weeks 6-12)**

###### **Goals**

- Improve muscle strength and endurance.
- Enhance neuromuscular control.
- Prepare for functional activities.

###### **Exercises**

- 1) Closed Kinetic Chain Exercises: Wall squats, step-ups, and lunges to strengthen the lower extremities.
- 2) Open Kinetic Chain Exercises: Leg press, hamstring curls, and calf raises.
- 3) Single-Leg Balance Exercises: Progress balance drills to more challenging surfaces (foam, balance boards).
- 4) Mini-Band Exercises: Sidesteps, monster walks, and clamshells to target hip muscles.
- 5) Plyometric Exercises: Jumping drills (e.g., vertical jumps, box jumps) when appropriate for the patient's recovery stage.

##### **Phase 4: Advanced Neuromuscular Control (Months 3-6 and beyond)**

###### **Goals**

- Enhance proprioception and dynamic stability.
- Prepare for sports-specific movements.

###### **Exercises**

- 1) Agility Drills: Cone drills, ladder drills, and agility ladder work.
- 2) Cutting and Pivoting Drills: Progress from controlled movements to sharper cuts and pivots.
- 3) Sport-Specific Drills: Tailor exercises to mimic the demands of the patient's specific sport.
- 4) Strength Maintenance: Continue strength training while emphasizing functional movements.
- 5) Core Strengthening: Incorporate core exercises to improve trunk stability.

#### **F. Methodology**

##### **1) Research Design**

- As our objective is to examine the effectiveness of proprioceptive training exercises after ACL injury, we should begin from PHASE 2 moderate protection phase of ACL rehabilitation.
- We are selecting some of the patients who had ACL injuries between 20 to 50 years of age.
- We are going to make them undergo proprioceptive training exercises as a part of ACL rehabilitation to achieve our objective to improve proprioception, balance, and stability for a certain duration.
- Our type of research design is EXPERIMENTAL STUDY where we are selecting all the ACL injury patients and examining them.
- Our plan of care is the proprioceptive training after ACL injury, and we are going to examine the effectiveness of the same.
- We are taking 5 different cases of ACL injuries whose age ranges from 20 - 40 years, having different histories.
- Out of all the 5 patients, we are going to apply our plan of care to all of them.
- Inclusion and Exclusion criteria are the same as mentioned above.
- All the cases have been treated for one and a half months. There are 5 sessions per week that include daily 1.5 hours session.

##### **2) Sampling Technique**

###### **1) Selection of Patient**

- Identify patients who require rehabilitation due to specific conditions or injuries.
- Assess their medical history, physical condition, and any contraindications.

**2) Examination of the Patient**

- Conduct a thorough assessment of the patient’s physical abilities, limitations, and functional goals.
- Evaluate joint range of motion, muscle strength, proprioception, and overall fitness.

**3) Balance and Stabilization Training Exercises**

- Focus on improving proprioception, balance, and joint stability.
- Exercises may include single-leg stance, wobble board drills, and stability ball exercises.

**4) Plyometric Exercises**

- Plyometrics involve rapid muscle lengthening followed by rapid shortening, enhancing explosive performance.
- These exercises can improve power, jump height, and neuromuscular control.

**5) Speed and Agility Training Exercises:**

- Enhance agility, coordination, and quick movements.
- Drills like ladder drills, cone drills, and shuttle runs are beneficial.

**6) Cardio Pulmonary Conditioning Exercises:**

- Improve cardiovascular endurance and overall fitness.
- Activities such as cycling, treadmill walking, or swimming can be part of this phase.

**Case Details**

**A. Patient 1**

A 25-year-old male with chief complaints of pain around the left knee, inability to sit with legs crossed, and pain while walking. The patient fell down from a height of around 3 feet ten months ago, twisting his left knee. Despite initial treatment, the pain persisted. MRI revealed an ACL tear in the left knee, leading to arthroscopic knee surgery. The patient continues to experience pain, swelling over the left foot and knee, and uses crutches for ambulation.

**B. Patient 2**

A 30-year-old male with pain during movements and walking over his left knee. The injury occurred two months ago due to slipping on the road, resulting in a lateral twisting of the left knee. After an

MRI diagnosis of an ACL tear, the patient underwent arthroscopic repair. Swelling, a scar around the left knee, and reliance on crutches for ambulation are observed. Reduced muscle strength in the left knee, limited ankle plantar flexion, limp in gait, muscle spasm, and tenderness are noted.

**C. Patient 3**

A 26-year-old male involved in an accident, presenting with mild pain and difficulty climbing stairs. The affected knee locked, rendering it impossible to bend. ACL reconstruction surgery was performed. The patient experiences pain, a 1 cm scar on the left knee, swelling, and pain aggravated by bending the knee. Rest provides relief.

**D. Patient 4**

A 31-year-old male with an ACL tear in the left knee, reporting inability to fully extend and bend the knee. Surgical reconstruction was done following a road traffic accident. Examination reveals differences between the left and right knee, reduced muscle power in both flexors and extensors, and a limited range of motion in the left knee extension. The patient exhibits a mesomorph body type, a visible surgical scar, and normal muscle tone but reduced patellar movement.

**E. Patient 5**

A 22-year-old male with complaints of pain in the right knee and difficulty bending it completely. A road traffic accident resulted in a right knee injury, leading to ACL reconstruction surgery. On examination, warmth around the joint, mild flexion of the right knee, independent gait, and reduced extensor strength in the right knee are observed. MRI confirms a complete ACL tear.

**Practical Guidelines Developing Individualized Protocols**

**A. Proprioception and Strength Program for ACL Injury**

Over the last several years, we have had good luck in avoiding ACL injuries in girl soccer players with a simple program outlined here. It’s not based on clinical trials, but on practical experience and guesswork.

**Table I: Different Exercises**

Exercises	Why	Examples
Closed eyes standing balance	Improved proprioception and strengthening of muscles supporting knee and ankle joints from a static situation	Stand on one leg, put foot from other leg behind knee of standing leg, close eyes. Balance for 60 seconds. Repeat with other leg.
Balance pad exercises	Improved proprioception and strengthening of muscles supporting knee and ankle joints from both static and dynamic situations	Single leg squats on Airex Balance Pad. Double leg squats. Single leg standing balance eyes open, eyes closed. Two players, each standing on a balance pad with one leg, throw a small heavy ball back and forth.
Band work for hamstring development	High school age players often have quads that are much more developed than hamstrings. Some studies suggest that this is a contributory factor to incidence of knee injury.	Band exercises, individual and with partner, providing band resistance to movement of ankle to buttocks. Can be done standing, leaning, or on hands and knees with one leg extended horizontally.

Stopping technique	A large proportion of ACL injuries witnessed in girls in match play have come at the end of runs where the player was slowing down after crossing the ball or making a run. Players train to use two and three step stopping from runs instead of making wrenching single step stops. After practicing the technique in isolation, literally by walking through the steps, a variety of stopping games can be used, such as red light - green light.	Variety of stopping games, such as red light - green light, after practicing the two and three step stopping technique.
General leg strength	Presumption that strong and symmetric leg muscles will provide better support for knee and ankle joints and make it possible for the athlete to recover from momentary lack of attention to joint position or from stepping on another player's foot or in a hole.	Monster walk with Gambetta bands. Side to side (sideways) walking with bands. Backward walking with bands. Carioca and slalom runs. Plyometric exercises for the legs. Single and double leg hops. Footwork exercises. Running hills. Harness work with partner providing resistance. Carrying partner on back over 40-yard course.
General aerobic fitness	Presumption that players with higher aerobic fitness will be less likely to experience momentary mental lapses late in matches leading to a poor one-step stop or poor slowdown at the end of a run.	Increased practice intensity, additional ball skill relays with running, end of practice team running competitions at match realistic distances, interval runs (also known as doggies or suicides). Post scrimmage match-related running to build and demonstrate fitness that could extend into overtime periods.

The important elements are listed in the table below. For more details, refer to the exercises and photos in protecting the athlete's knee.

### B. Balance Pad and Bands

Balance pads are appearing to be made of multiple layers of foam rubber, each layer of varying density. The outer shell of the balance pad is made of closed cell foam or a similar synthetic product that does not adsorb water. Although wobble boards were well established and have shown proven benefits, balance pads may be more appropriate for soccer coaches and their players. First, the entire balance pad is flat, and its action or reaction to the athlete's movements will not dismount the athlete forcefully. Second, because the pad is flat and soft, it can be introduced and used regularly at the soccer field on the turf, yet still be used daily at home on carpet, linoleum, on the back deck, or in the basement fitness area.

### Results

#### A. Case 1

- The patient has shown improvement in proprioception, balance, and stability while standing on an unstable surface and during walking on uneven terrain.
- Gradually increasing walking distance and speed is recommended.
- Incorporating more demanding functional activities such as stair climbing, jogging, and agility drills is beneficial.

#### B. Case 2

- Similar to Case 1, the patient has improved proprioception, balance, and stability.
- Continue incorporating functional activities like stair climbing, jogging, and agility drills.

#### C. Case 3

- Focus on progressively incorporating demanding functional activities, including stair climbing, jogging, and agility drills.

#### D. Case 4

- Unfortunately, the patient has not regained full range of motion (ROM) and is not incorporating demanding functional activities.
- Further rehabilitation strategies may be needed.

#### E. Case 5

- The patient has improved proprioception, balance, and stability while standing on an unstable surface and walking on uneven terrain.
- Gradually increasing walking distance and speed is recommended.
- Continue incorporating demanding functional activities like stair climbing, jogging, and agility drills.

### Discussion

#### A. Success Rate

- Out of the 5 ACL injury patients, 2 have successfully recovered and shown significant improvement.
- 1 patient demonstrated mild improvement.
- 1 patient exhibited moderate improvement.
- Unfortunately, the treatment technique was ineffective for a single patient.

#### B. Uniform Treatment Approach

- It's noteworthy that we applied the same treatment plan to all patients, beginning with an examination of each patient.
- Consistency in the initial assessment allows for a fair comparison of outcomes.

#### C. Individual Variability

- The varying responses highlight the individual nature of rehabilitation.
- Factors such as pre-existing conditions, severity of injury, and patient compliance can influence outcomes.

#### D. Refining Treatment Strategies

- For the patient who did not respond well, consider adjusting the treatment plan.
- Reevaluate the specific exercises, intensity, and progression.
- Collaborate with colleagues or seek expert opinions to tailor interventions.

#### E. Long-Term Monitoring

- Continue monitoring progress for all patients.
- Adjust interventions based on ongoing assessments.
- Celebrate successes and adapt strategies for challenges.

Our plan of treatment was same for the all the patient like we have started with examination of patient followed by

#### **F. Balance and Stabilization Exercises**

- These exercises play a crucial role in enhancing proprioception and stability.
- Focusing on balance challenges, such as standing on an unstable surface, helps activate proprioceptive pathways.
- Consider incorporating single-leg balance exercises, proprioceptive boards, and stability ball drills.

#### **G. Plyometrics Training Exercises**

- Plyometrics involve explosive movements to improve power, strength, and coordination.
- For ACL rehabilitation, controlled plyometric exercises can enhance neuromuscular control.
- Examples include box jumps, lateral hops, and squat jumps.

#### **H. Speed and Agility Training Exercises**

- These exercises simulate real-life movements and enhance dynamic stability.
- Include ladder drills, cone drills, and change-of- direction exercises.
- Gradually progress from slow to high-intensity movements.

#### **I. Cardio-Pulmonary Conditioning Exercises**

- Cardiovascular fitness is essential for overall health and recovery.
- Low-impact activities like stationary cycling, swimming, or elliptical training can improve endurance.
- Monitor heart rate and gradually increase exercise duration.

### **Conclusion**

The study focused on assessing the effectiveness of proprioceptive training exercises following ACL injury and reconstruction surgery. The results revealed that the impact of these exercises on strength, balance, agility, speed, and overall fitness varies significantly. Patient age, injury severity, and pre-morbid status play crucial roles in determining the outcomes.

#### **A. Effectiveness of Proprioceptive Training**

- Your study aimed to examine the effectiveness of proprioceptive training exercises after ACL injury and reconstruction surgery.
- Results indicate that improvement in strength, balance, agility, and speed, as well as overall fitness, varies based on factors such as patient age, injury severity, and pre-morbid status.

#### **B. Successful Completion**

- Congratulations on successfully completing this project with the guidance of your lectures and project guide.
- Your effort to include essential information for others is commendable.

#### **C. Open to Suggestions**

- Welcoming suggestions for further improvement show your commitment to enhancing the project.
- Collaboration and continuous refinement are essential for advancing research and patient care.

### **Future Direction**

#### **A. Emerging Technologies**

According to a recent meta-analysis of youth resistance training, increasing muscular strength is contingent on proper volume to offer adequate adaptive stimulus, and resistance training is an effective strategy for motor performance in children and adolescents [12]. The current study's findings clearly show that engagement in physical activity should not begin with competitive sport, but rather with well-rounded preparatory fitness training that is gradually improved over time. Teachers and coaches can

be better equipped to ensure that youth see greater gains in both health- and skill-related physical fitness, as well as a reduction in the risk of sports-related injury, by incorporating integrative NMT into physical education classes, after-school activities, and sport practice sessions [13].

One study used a 10- to 15-minute preventive NMT program three or four times per week to assess motor learning retention in the lower extremities [14]. Another study compared jump-landing movement patterns in 3- month and 9- month groups and found that the 9-month group retained the learned landing movement patterns 3 months after an ACL prevention training program, whereas the 3-month group's landing movement patterns returned to prestudy levels after 3 months without training [15].

The long-term repercussions of ACL damage are visible in the prevalence of OA in the injured knee, which occurs in 41% to 51% of injured knees compared to 4% to 8% in uninjured soccer players' legs. [16] Meniscus damage and subsequent surgery have a long-term impact on knee joint health. Several studies that conducted follow-up reports on meniscus surgery patients found that around 50% have knee OA, joint pain, and dysfunction [16].

Although the incidence of anterior cruciate ligament (ACL) injury is uncertain [17] 350,000 ACL reconstructions (ACLRs) are performed in the United States each year [18]. Plyometrics Plyometrics that emphasize good technique and body mechanics can aid in the prevention of significant ligamentous injuries, particularly ACL tears [19, 20].

### **B. Ongoing Research**

Anterior cruciate ligament (ACL) injuries are common and debilitating, particularly in athletes. Despite significant advancements in ACL injury prevention, rehabilitation, and reconstruction techniques, there remain several areas requiring further investigation and potential future research directions. Key areas of focus:

**Biomechanics and ACL Injury Risk:** Understanding the biomechanical factors that contribute to ACL injury is crucial for developing effective prevention strategies. This includes investigating the role of neuromuscular control, lower extremity alignment, and specific movement patterns in ACL injury risk [29, 30].

#### **C. Biological Factors and ACL Healing**

ACL healing is a complex process that involves various biological factors, including inflammation, cell proliferation, and extracellular matrix remodeling. Elucidating the role of these factors can lead to the development of novel therapeutic approaches to enhance ACL healing and reduce the risk of re-injury [31,32].

#### **D. Graft Selection and Optimization**

ACL reconstruction often involves the use of autografts, allografts, or artificial grafts. Research is needed to optimize graft selection, preparation, and fixation techniques to improve graft survival and long-term functional outcomes [33, 34].

#### **E. Return-to-Sport Protocols**

Current return-to-sport protocols are based on objective measures of knee stability and strength but may not adequately capture the psychosocial factors and individual risk factors that influence successful return to sport. Developing personalized return-to-sport protocols that consider these factors is essential [35, 36].

#### **F. Long-Term Outcomes and Osteoarthritis Risk**

ACL injuries have been associated with an increased risk of developing osteoarthritis (OA) later in life. Understanding the mechanisms underlying this association and identifying strategies to mitigate the risk of OA is a critical area of research [37, 38].

### G. Genetic and Epigenetic Factors

Emerging research suggests that genetic and epigenetic factors may play a role in ACL injury risk and healing. Investigating these factors could lead to personalized risk assessment and treatment strategies [39, 40].

### H. Role of Technology in ACL Injury Prevention and Rehabilitation

Technology, such as wearable sensors and virtual reality, has the potential to revolutionize ACL injury prevention and rehabilitation. Research is needed to develop and validate technology-based interventions that can effectively reduce injury risk and optimize recovery [41, 42].

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