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Review Article

Anterior cruciate ligament injury prevention: An evidence-based approach from mechanism to implementation

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Abstract

The objective is to analyse ACL injury mechanisms, evaluate risk factors, and present evidence-based prevention strategies applicable to both general population and athletes, while developing a practical, time-efficient training program. The anterior cruciate ligament (ACL) is crucial for knee stability. With an incidence rate of 68.6 per 100,000 population and female athletes showing 2-8 times higher risk, ACL injuries represent a significant healthcare burden, often leading to early-onset osteoarthritis and reduced athletic participation. We reviewed literature focusing on ACL injury mechanisms, risk factors, and prevention strategies, synthesizing the information to develop a structured prevention program incorporating dynamic warm-up, strengthening exercises, and plyometric training. Most ACL injuries occur during non-contact situations, primarily during dynamic tasks. Prevention programs demonstrated 60-88% injury reduction rates. Our compiled program emphasizes a progressive approach over 4 weeks, requiring 15-20 minutes per session, 2-3 times weekly, including:
1. Dynamic warm-up exercises; 2. Strengthening exercises; 3. Progressive plyometric training these components showed improvement in neuromuscular control and biomechanical efficiency.
Implementation of structured prevention programs significantly reduces ACL injury risk while improving performance metrics. Success requires proper technique, consistent participation, and appropriate progression. Future research should focus on improving program compliance and developing population-specific modifications.

Keywords: Anterior cruciate ligament, Injury prevention, Neuromuscular training, Exercise program.

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1. Introduction

The anterior cruciate ligament (ACL) plays a crucial role in maintaining knee stability. As one of the two cruciate ligaments, it originates from the anteromedial aspect of the intercondylar region of the tibial plateau and extends posterolaterally to attach to the medial aspect of the femoral condyle. The ACL consists of two distinct bundles: an isometric anteromedial bundle and a posterolateral bundle with more versatile length changes.[1]

The anteromedial bundle is tightest in flexion and primarily responsible for anterior tibial translation, providing about 85% of stability. In contrast, the posterolateral bundle is tightest in extension and acts as a secondary restraint, offering medial, lateral, and rotational stability.[2,3]

ACL injuries have become increasingly common, affecting both the general population and athletes. Studies indicate an overall incidence rate of 68.6 per 100,000 population.[4] These injuries often lead to significant consequences, as ACL-deficient knees are more susceptible to the progression of arthritis and further injuries to chondral and meniscal structures. ACL injuries account for approximately 50% of all knee injuries, with most requiring surgical repair, resulting in substantial financial burden and significant mental and physical impact on individuals. Many athletes have been forced to abandon their sports careers due to ACL injuries, unable to return to their previous fitness levels even after surgery, often due to the fear of reinjury.[5]

Research spanning a decade, conducted by Hewett et al., examined both male and female young athletes using coupled biomechanical epidemiological approaches.[6] A notable

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finding is that female athletes experience a two to eightfold higher incidence of ACL injuries compared to their male counterparts.[7,8] This comprehensive review aims to educate the general population, uniformed officers, and athletes about the vital role of ACL in daily activities and sports-related movements, while also raising awareness about injury incidence, consequences, and preventive strategies to minimize ACL injury risk, ultimately reducing financial burden and improving individual physical and mental well-being.

Our focus will be on examining injury mechanisms widely recognized worldwide and presenting preventive programs that can be implemented by both the general population and athletes, whether at home or in training facilities, without time constraints.

2. Methodology

Research Analysis of Injury Mechanisms: Studies analyzing sports-related footage have identified that most ACL injuries occur during non-contact dynamic tasks, including single-leg landings, sudden decelerations, and rapid directional changes.[9-15] These injuries typically occur shortly after initial contact when the knee joint experiences significant valgus and rotational forces (both external and internal), combined with high mechanical loads.[10-15]

2.1. Risk factor assessment

1. Intrinsic risk factors
   a. Anatomical parameters:
      i. Tibial factors
         - Increased posterior tibial slope correlates with increased tibial translation over femur.[16,17]
         - Medial tibial plateau depth (MTPD) - Greater depth prevents tibial translation
      ii. Notch parameters:
         - Notch width index below 0.29 associates with higher risk[18]
         - 'A' shaped femoral notch shows stronger correlation with ACL injury[19]

   b. Gender-specific factors: Females demonstrate higher risk[20] due to:
      i. Anatomical variations
      ii. Neuromuscular variations including:
         - Ligament dominance
         - Quadriceps dominance
         - Leg dominance
         - Trunk dominance
         - Different movement and muscle activation patterns
         - Greater knee laxity
         - Smaller intercondylar notch

   c. Hormonal factors: Higher injury rates observed in the preovulatory phase due to elevated estrogen levels[21]
   d. Genetic predisposition:
      i. Two-fold higher risk with family history[22]
      ii. Mutations identified in:
         - COL1A1[23]
         - COL5A1[24]
         - COL12A1[25]
         - Chromosome 11q22

   e. Cognitive factors: Reduced neurocognitive performance correlates with decreased neuromuscular control and coordination issues.[26]
   f. Previous injury history: Eleven-fold higher risk, with previous ankle injuries showing significant correlation[27]

2. Extrinsic risk factors
   a. Environmental conditions:
      i. Weather impacts:[28,29]
         - Wet conditions reduce surface friction
         - Hot weather increases ligament extensibility
      ii. Playing surface variations:
         - Bermuda grass shows higher injury incidence[30]
         - Synthetic courts demonstrate 2-35 times higher risk compared to wooden surfaces[31]

2.2. Biomechanical analysis

The research examined forces across different planes:

1. Frontal plane: Both valgus and varus forces can increase ACL load,[32,33] with valgus collapse being the most common mechanism.
2. Transverse plane: Internal rotation moments of the tibia relative to the femur create higher ACL loads compared to external rotation.[32,33]
3. Non-sagittal plane movements have greater impact on ACL loading when occurring simultaneously with anterior shear force.[32-34]

This methodological approach provided a comprehensive understanding of ACL injury mechanisms and risk factors, forming the foundation for developing effective preventive strategies. The combination of video analysis, biomechanical studies, and risk factor assessment has enabled the development of targeted intervention programs.

3. Discussion

3.1. Muscular influence on ACL loading

1. Quadriceps function
   a. Acts as an antagonist to ACL
      i. In lower knee flexion (30-50 degrees), quadriceps activation induces:

- ACL loading[36,37]
- Anterior shear force[38]
- Anterior tibial translation[39]
- Knee valgus rotation[39,40]
- Knee valgus moment[38]
- Tibial internal rotation[39,40]

ii. At higher knee flexion angles, quadriceps impact on ACL loading diminishes due to altered patellar tendon and tibial axis angles.

2. Hamstring contribution
   a. Generates posterior shearing force at tibia[36,43]
   b. Studies demonstrate protective effects through:
      - Reduction in ACL strains and forces[44,45]
      - Decreased anterior shearing forces[46,47]
      - Limited anterior tibial translation[46]
      - Reduced internal tibial rotation[46,48]
   c. In frontal plane movements, medial and lateral hamstrings influence varus and valgus loading respectively during sidestep cutting and single leg landing
   d. Biceps femoris shows greatest ACL protection through opposition to internal knee rotation[49]

3. Gastrocnemius impact
   a. In vivo studies demonstrate increased ACL strain through direct electrical stimulation at knee flexion angles of 15, 30, and 45 degrees compared to relaxed state[42]

4. Soleus effect:
   a. Induces posterior tibial translation[41]

5. Additional muscular influences
   a. Gracilis and Sartorius create posterior shear at tibia beyond 30 degrees of knee flexion.

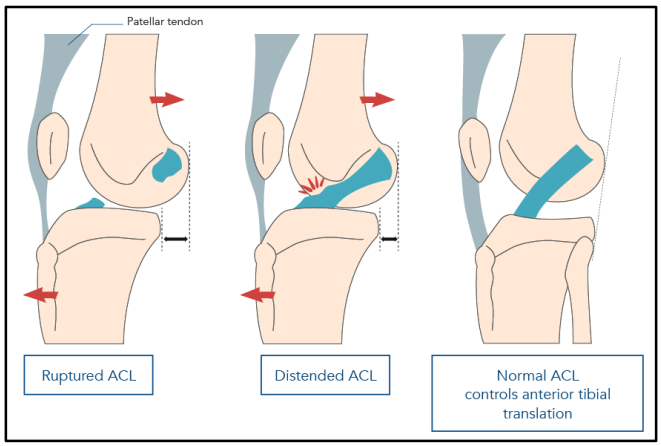

Figure 1: Illustration of ACL injury mechanism

3.2. Preventive strategy implementation

Most ACL injuries occur through non-contact or indirect contact mechanisms involving uncontrolled lower extremity biomechanics. Effective prevention requires comprehensive training programs focused on neuromuscular control and lower extremity biomechanics.[50,51] Key findings include:

1. Program effectiveness
   a. Sadoghi et al. demonstrated 62% reduction in ACL injury risk through combined plyometric, strength, agility, and balance training
   b. Hewett et al. reported 60% risk reduction through pre-planned motor skills training focusing on lower extremity alignment[52]

2. Component integration
   a. National Athletic Trainer's Association recommends multicomponent injury prevention programs[53]
   b. Sanford knee injury prevention program emphasizes hip muscle activation to reduce dynamic knee valgus[54]

3. Program success rates
   a. PEP (Prevent injury and enhance performance) program: 88% injury reduction[55]
   b. Harmoknee program: 70% reduction in football players[56]
   c. Neuromuscular training: 70% reduction in non-contact ACL injuries[57]
   d. Multi-component programs: 73.4% reduction in non-contact ACL injuries[58,59]

4. Performance enhancement
   a. Studies demonstrate improvements in:
      - Ground reaction forces[60-64]
      - Balance and stability[65]
      - Muscle strength
      - Athletic performance
      - Neuromuscular control
      - Biomechanical efficiency

The collective evidence supports implementing comprehensive prevention programs incorporating multiple training components, with documented success in both injury reduction and performance enhancement. These programs show particular effectiveness when including progressive overload principles and specific attention to proper movement patterns.

This discussion establishes the foundation for developing targeted prevention strategies that can be effectively implemented across various populations, from general fitness enthusiasts to competitive athletes.

3.3. Recommended prevention program

Based on the comprehensive review of successful intervention strategies, we propose a structured, feasible training program that can be implemented both at home and in training facilities. The program design considers time constraints of modern lifestyles while maintaining effectiveness.

1. Program structure
   a. Duration: 15-20 minutes per session
   b. Frequency: 2-3 times per week
   c. Progressive implementation over 4 weeks

2. Phase implementation
   a. Initial phase (Weeks 1-3): Focus on:
      i. Dynamic warm-ups targeting core activation
      ii. Lower extremity strength development
      iii. Patellofemoral load management exercises

   b. Advanced phase (Week 4 onwards): Integration of
      i. Basic program components
      ii. Progressive plyometric exercises
      iii. Advanced neuromuscular training

Table 1: Compiled training programme

Dynamic warm UP (5 Minutes)	**Strengthening (10 Minutes)**	**Plyometrics (10 Minutes) Week 4**
High knees*10	Single leg dead lift walk*10	Double leg lateral hops
Butt kicks*10	Superman*10	Double leg vertical jumps
Figure of 4*10 seconds (both)	Lateral lunge*10(each side)	Double leg long jump
Backward running	Side plank with leg lift (*10) each side	Single leg hop with 90degree turn
Side walking progressive to side running		

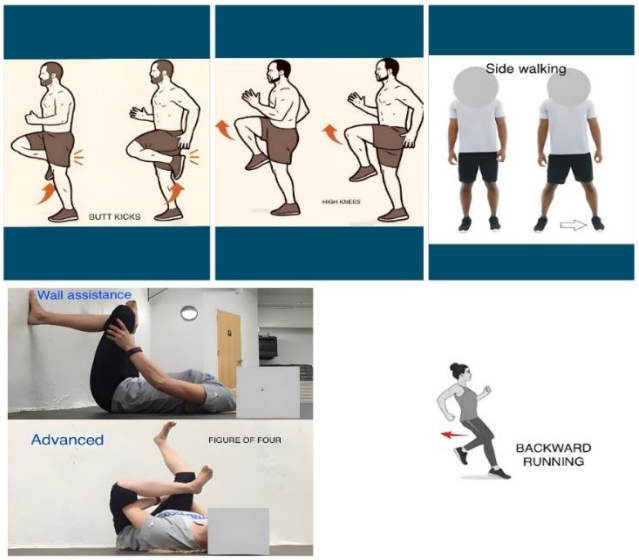

Figure 2: Dynamic warm up

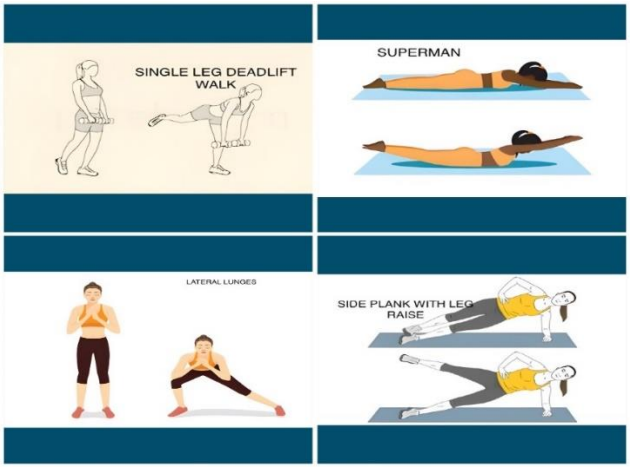

Figure 3: Strengthening exercises

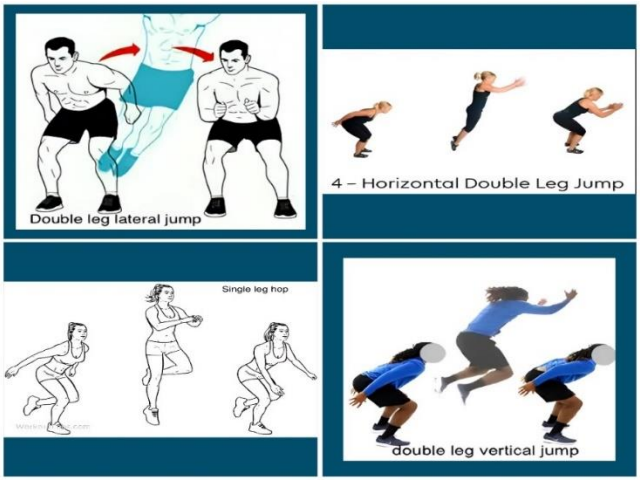

Figure 4: Plyometric exercises

3.4. Key program components and progression

1. Dynamic warm-up:
   a. Purpose: Neuromuscular activation and movement preparation
   b. Focus on proper form and controlled movement
   c. Progressive increase in speed and complexity

2. Strengthening exercises:
   a. Emphasis on core stability and lower extremity strength
   b. Proper alignment during single-leg activities
   c. Progressive load increase based on individual capacity

3. Plyometric training (Week 4 onwards):
   a. Introduction after establishing baseline strength
   b. Focus on landing mechanics and control
   c. Progressive increase in intensity and complexity

3.5. Implementation guidelines

1. Safety considerations
   a. Proper form must be maintained throughout all exercises

b. Progress only when movement control is demonstrated
c. Monitor fatigue levels and adjust accordingly

2. Progressive overload:
   a. Gradual increase in:
      - Exercise complexity
      - Number of repetitions
      - Movement speed
      - Impact intensity

3. Monitoring and adaptation:
   a. Regular assessment of movement quality
   b. Individual progression based on performance
   c. Modification based on specific needs and goals

This program synthesizes evidence-based components from successful prevention strategies[50-59] while maintaining practicality for various populations. The structured progression allows for safe advancement while building necessary strength and control for injury prevention.

3.6. Key success factors:

1. Consistent participation
2. Proper form maintenance
3. Appropriate progression
4. Regular monitoring
5. Individual adaptation as needed

The program should be implemented under proper guidance initially to ensure correct form and understanding of progression principles. This approach has shown significant success in reducing ACL injury risk while improving overall performance metrics.

4. Conclusion

Based on the comprehensive review of ACL injury mechanisms, risk factors, and preventive strategies, several key conclusions can be drawn:

1. Understanding ACL injury risk:
   a. ACL injuries remain a significant concern in both athletic and general populations
   b. Female athletes face higher risk
   c. Multiple risk factors, both intrinsic and extrinsic, contribute to injury occurrence

2. Prevention program effectiveness:
   a. Multi-component training programs show significant success in reducing ACL injury risk
   b. Documented reduction rates range from 60-88% when programs are properly implemented
   c. Benefits extend beyond injury prevention to include:
      - Improved performance metrics
      - Enhanced neuromuscular control
      - Better biomechanical efficiency
      - Increased overall strength and stability

3. Implementation success factors:
   a. Early intervention and education
   b. Consistent program adherence
   c. Proper technique and progression
   d. Regular monitoring and adaptation
   e. Integration into regular training routines

4. Future considerations:
   a. Need for continued research into personalized prevention strategies
   b. Development of sport-specific modifications
   c. Integration of new technologies for movement assessment
   d. Focus on compliance enhancement strategies

The evidence strongly supports the implementation of structured prevention programs across all populations at risk for ACL injury. The recommended program provides a practical, time-efficient approach that can be adapted to various settings and skill levels. Success in reducing ACL injury risk requires commitment from both practitioners and participants, with emphasis on proper form, consistent participation, and appropriate progression.

4.1. Key recommendations

1. For athletes:
   a. Integrate prevention programs into regular training routines
   b. Focus on proper technique during all athletic movements
   c. Maintain consistent participation in prevention programs

2. For healthcare providers:
   a. Implement early screening for risk factors
   b. Provide proper education about injury prevention
   c. Monitor and adjust programs based on individual progress

3. For general population:
   a. Engage in regular preventive exercises
   b. Focus on proper movement patterns in daily activities
   c. Maintain consistent physical activity levels

Through proper implementation of these evidence-based strategies, significant reduction in ACL injury risk can be achieved, leading to improved long-term joint health and sustained physical activity participation across all populations.

This comprehensive approach to ACL injury prevention represents a significant step forward in protecting joint health and maintaining active lifestyles for both athletes and the general population. The success of these programs demonstrates that with proper education, implementation, and adherence, the risk of ACL injury can be substantially reduced, leading to better outcomes for all participants.

4.2. Detailed recommendations

1. For athletic population:
   a. Pre-season implementation
      i. Mandatory screening for risk factors including:
         - Biomechanical assessment
         - Strength evaluation
         - Movement pattern analysis
      ii. Introduction of prevention program 6-8 weeks before season
      iii. Focus on proper technique before advancing to complex movements

   b. In-season maintenance
      i. Integration of prevention exercises into regular warm-ups
      ii. Monitoring of fatigue levels and adaptation of program intensity
      iii. Regular reassessment of movement patterns

   c. Sport-specific modifications
      i. Customize exercises based on sport demands
      ii. Address specific movement patterns common in each sport
      iii. Include sport-relevant agility and reaction training

2. For healthcare providers:
   a. Assessment protocols
      i. Implement comprehensive screening tools
      ii. Regular monitoring of progress
      iii. Documentation of movement patterns and corrections

   b. Education components
      i. Provide clear explanation of injury mechanisms
      ii. Demonstrate proper exercise technique
      iii. Educate about progression criteria

   c. Program progression guidelines
      i. Establish clear criteria for advancement
      ii. Monitor and document progress
      iii. Modify programs based on individual response

3. For general population:
   a. Daily activity modifications
      i. Proper movement patterns during routine activities
      ii. Awareness of body positioning
      iii. Integration of basic strengthening exercises into daily routine

   b. Exercise program implementation
      i. Start with basic movements and proper form
      ii. Gradual progression based on comfort and capability
      iii. Regular practice of balance and stability exercises

4. Specific population considerations:
   a. Female athletes
      i. Additional focus on:
         - Hip strengthening
         - Landing mechanics
         - Core stability
         - Neuromuscular control

   b. Youth athletes
      i. Age-appropriate exercise modifications
      ii. Focus on fundamental movement patterns
      iii. Gradual progression of intensity

   c. Returning Athletes (Post-injury)
      i. Modified progression protocol
      ii. Additional focus on psychological readiness
      iii. Regular assessment of movement symmetry

5. Long-term adherence strategies:
   a. Program monitoring
      i. Regular assessment of technique
      ii. Documentation of progress
      iii. Feedback on movement quality

   b. Motivation enhancement
      i. Setting achievable goals
      ii. Tracking progress
      iii. Regular feedback sessions

   c. Program adaptation
      i. Periodic program updates
      ii. Variety in exercise selection
      iii. Progression based on individual capability

6. Environmental considerations:
   a. Training surface
      i. Proper footwear selection based on surface
      ii. Awareness of surface conditions
      iii. Adaptation of movement based on environment

   b. Equipment needs
      i. Minimal equipment requirements for accessibility
      ii. Alternative exercise options
      iii. Proper use of available resources

7. Success metrics
   a. Performance indicators
      i. Improvement in movement patterns
      ii. Enhanced strength and stability
      iii. Better neuromuscular control

   b. Compliance measures
      i. Regular attendance
      ii. Proper technique maintenance
      iii. Progression through program phases

These detailed recommendations provide a comprehensive framework for implementing ACL injury prevention strategies across different populations. The key to success lies in proper implementation, regular monitoring,

and appropriate progression based on individual capabilities and needs.

4.3. Implementation strategies

1. Foundational training phase (Weeks 1-3):
   a. Dynamic warm-up protocol (5 minutes):
      i. High knees:
         - 10 repetitions each leg
         - Focus on hip flexion and knee drive
         - Maintain upright posture
         - Progress from walking to running pace
      ii. Butt kicks:
         - 10 repetitions each leg
         - Emphasize hamstring activation
         - Maintain vertical shin position
         - Progress from walking to running pace
      iii. Figure of 4 stretches:
         - 10 seconds hold each side
         - Focus on hip external rotation
         - Maintain balance and control
         - Use support if needed initially
      iv. Backward running:
         - Start with small steps
         - Progress to longer distances
         - Focus on controlled movement
         - Emphasize toe-to-heel contact
      v. Side walking/running:
         - Begin with controlled side steps
         - Progress to side shuffle
         - Maintain hip level
         - Avoid crossing feet

   b. Strengthening exercises (10 minutes):
      i. Single leg dead lift walk:
         - 10 repetitions each side
         - Focus on hip hinge
         - Maintain neutral spine
         - Control through entire movement
      ii. Superman exercise:
         - 10 repetitions
         - Emphasis on core stability
         - Equal lift of arms and legs
         - Hold briefly at top position
      iii. Lateral lunges:
         - 10 repetitions each side
         - Keep knee aligned with foot
         - Maintain upright torso
         - Push through heel to return
      iv. Side plank with leg lift:
         - 10 repetitions each side
         - Focus on hip stability
         - Maintain neutral spine
         - Control leg movement

2. Advanced training phase (Week 4 onwards):
   a. Plyometric progression (10 minutes):
      i. Double Leg Lateral Hops:
         - Start with small distances
         - Focus on soft landings
         - Maintain knee alignment
         - Progress to longer distances
      ii. Double leg vertical jumps:
         - Begin with quarter jumps
         - Progress to half jumps
         - Focus on landing mechanics
         - Control descent phase
      iii. Double leg long jump:
         - Start with controlled jumps
         - Emphasize landing stability
         - Maintain proper alignment
         - Progress jump distance
      iv. Single leg hop with 90-degree turn:
         - Begin with 45-degree turns
         - Progress to 90 degrees
         - Focus on landing control
         - Maintain balance throughout

3. Progression guidelines:
   a. Movement quality checkpoints:
      i. Knee position:
         - Aligned with second toe
         - No medial collapse
         - Controlled movement
      ii. Hip control:
         - Minimal drop
         - Stable pelvis
         - Balanced movement
      iii. Core stability:
         - Neutral spine
         - Engaged core
         - Controlled movement

   b. Advancement criteria:
      i. Basic phase to advanced:
         - Perfect form in basic exercises
         - No pain during movement
         - Demonstrated control
         - Adequate strength base

4. Monitoring protocol:
   a. Weekly assessment:
      i. Movement quality:
         - Form check
         - Balance assessment
         - Control evaluation
      ii. Exercise progression:
         - Volume tolerance
         - Movement complexity
         - Individual adaptation

   b. Monthly review:
      i. Program effectiveness:
         - Strength gains
         - Movement improvement
         - Balance enhancement

5. Safety considerations:
   a. Exercise modification:
      i. Fatigue management:
         - Reduce volume if needed
         - Maintain quality over quantity
         - Rest periods as needed
      ii. Individual adjustments:
         - Based on fitness level
         - Account for previous injury
         - Consider movement patterns

5. Source of Funding

None.

6. Conflict of Interest

None.

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