Supplementary Material 1

Detailed Criteria-Based Rehabilitation Programme (Abstracted Content Framework)

Rationale for Supplementary Description

To enhance clinical applicability and reproducibility, rehabilitation content was retrospectively categorised into functional domains based on the original training process. Specific exercises, loading parameters, and proprietary implementation details are not disclosed; instead, emphasis is placed on the underlying movement patterns, neuromuscular targets, and progression strategies.

Overall Rehabilitation Principles

Rehabilitation followed a criterion-based, multi-domain progression model integrating neuromuscular control, strength development, and sport-specific loading.

Across all phases, key principles included:

- Symptom-guided load progression
- Emphasis on movement quality and joint control
- Integration of distal-to-proximal kinetic chain coordination
- Early incorporation of controlled dynamic tasks
- Continuous reassessment of joint response and functional performance

Phase 1: Early Protection and Neuromuscular Activation

Primary Objectives

- Joint homeostasis and effusion control
- Restoration of full knee extension
- Prevention of arthrogenic muscle inhibition
- Early neuromuscular activation

Rehabilitation Content

Neuromuscular Activation

- Isometric quadriceps activation with emphasis on terminal knee extension control
- Early hamstring co-contraction strategies to support anterior tibial control
- Low-amplitude sagittal plane joint control tasks within restricted ROM

Movement and Control

- Bilateral closed-chain loading in protected ranges

- Controlled foot and ankle activation as distal starting point for kinetic chain integration
- Basic step-based stabilisation patterns under predictable conditions

Strength Development

- Low-load closed-chain strengthening targeting quadriceps and hip stabilisers
- Early posterior chain activation (hip extension patterns)
- Trunk stabilisation focusing on frontal plane pelvic control

Conditioning

- Low-impact cyclic loading (cycling, aquatic therapy)
- Maintenance of general physical conditioning without joint overload

Phase 2: Progressive Load Tolerance and Movement Control

Primary Objectives

- Restoration of full ROM
- Development of dynamic knee stability
- Progressive load tolerance under functional conditions

Rehabilitation Content

Neuromuscular Control

- Progression from sagittal to multiplanar control strategies
- Distal-to-proximal integration (foot/ankle → knee → hip)
- Step-based stabilisation drills with increasing variability
- Perturbation-like tasks under controlled conditions
- Emphasis on frontal-plane knee alignment and varus–valgus control

Strength Development

- Transition to concentric–eccentric loading
- Development of unilateral load tolerance
- Integration of quadriceps-dominant and posterior chain loading
- Targeted terminal knee extension control
- Progressive velocity-based strengthening (e.g. controlled isokinetic work)

Movement Patterns

- Split-stance and lunge-based loading

- Step-up and vertical force transfer tasks
- Single-leg stance and dynamic balance tasks
- Controlled introduction of rotational components

Plyometric Preparation

- Introduction of low-amplitude elastic loading
- Emphasis on landing mechanics, load distribution, and joint alignment
- Controlled bilateral jumping tasks

Conditioning

- Progressive aerobic conditioning (cycling, treadmill)
- Introduction of interval-based loading
- Gradual reintroduction of cyclic gait mechanics

Phase 3: Sport-Specific Strength, Speed, and Plyometric Preparation

Primary Objectives

- Development of high-force and high-velocity capacity
- Preparation for multidirectional sport demands
- Enhancement of reactive neuromuscular control

Rehabilitation Content

Strength and Power

- Maximal and explosive strength development
- Rate of force development under sport-specific conditions
- Advanced unilateral loading strategies

Plyometrics

- Progression to higher amplitude and reactive tasks
- Bilateral → unilateral jumping and landing
- Vertical → horizontal → multidirectional loading
- Emphasis on reactive stiffness and rapid force absorption

Running and Change of Direction

- Linear running progression to multidirectional movement
- Acceleration and deceleration mechanics

- Gradual introduction of cutting and pivoting tasks

Neuromuscular Control

- High-speed coordination under reduced predictability
- Integration of trunk control into dynamic sport-specific tasks
- Maintenance of frontal-plane knee stability under load

Phase 4: Return to Training and Competition Integration

Primary Objectives

- Reintegration into sport-specific training
- Exposure to unpredictable and contact situations
- Preparation for competitive demands

Rehabilitation Content

Sport-Specific Integration

- Progressive transition from controlled drills to open environment tasks
- Integration of decision-making under physical load
- Exposure to sport-specific technical and tactical demands

High-Demand Loading

- Acceleration–deceleration sequences
- Cutting, pivoting, and reactive movement patterns
- Gradual exposure to contact scenarios

Load Management

- Progressive increase in training volume and intensity
- Monitoring of fatigue response and joint reactivity
- Ongoing adjustment based on clinical and performance feedback

Summary of Rehabilitation Content (Table A)

Rehabilitation was characterised by an early integration of neuromuscular control, progressive development of load tolerance, and systematic transition toward sport-specific demands.

A key feature of this approach was the early introduction of controlled dynamic and elastic loading, combined with continuous emphasis on movement quality and joint stability across all phases.

This structured yet adaptable framework enabled safe progression toward unrestricted sport participation while minimising reinjury risk.

Domain	Phase 1	Phase 2	Phase 3	Phase 4
Joint Homeostasis	Effusion control, protected ROM, avoidance of anterior tibial translation	Stable joint response under increasing load	Maintained under high-load conditions	Maintained under sport-specific load
Neuromuscular Control	Isometric activation, co-contraction strategies, sagittal plane control	Multiplanar control, perturbation-based stabilisation, distal-to-proximal integration	High-speed neuromuscular coordination, reactive control	Open-skill control under unpredictable conditions
Quadriceps Function	Isometric activation, terminal extension control	Concentric–eccentric strengthening, end-range control	Maximal and explosive force production	Integrated into sport-specific tasks
Posterior Chain (Hamstrings & Hip)	Early co-contraction, low-load activation	Progressive eccentric loading, hip-dominant patterns	High-load and high-velocity force production	Dynamic stabilisation during high-speed tasks
Movement Patterns	Bilateral closed-chain patterns, constrained ROM	Unilateral loading, split stance, controlled rotation	Complex multi-joint patterns under load	Fully integrated sport-specific movement patterns
Frontal Plane Control	Basic alignment control in static conditions	Dynamic varus–valgus control in single-leg tasks	Maintained during high-speed and plyometric tasks	Maintained under reactive and contact conditions
Rotational Control	Low-load internal/external control of knee	Controlled rotational tasks under load	High-speed rotational stability	Sport-specific pivoting and cutting
Plyometric / Elastic Load	Not applied	Low-amplitude, controlled bilateral tasks (landing focus)	High-amplitude, reactive, unilateral and multidirectional tasks	Fully integrated into sport-specific actions
Running / Locomotion	Not applied	Gait retraining, gradual cyclic loading	Linear → multidirectional running, acceleration/deceleration	Full sport-specific locomotion
Change of Direction (COD)	Not applied	Low-intensity directional changes	Progressive COD under increasing speed and complexity	High-speed, reactive COD under game conditions

Core / Trunk Control	Static stabilisation, pelvic control	Dynamic trunk control integrated into lower-limb tasks	High-load and high-speed trunk stabilisation	Integrated into sport-specific and reactive tasks
Conditioning	Low-impact aerobic (cycling, aquatic)	Progressive aerobic and interval-based conditioning	High-intensity conditioning integrated with movement tasks	Full conditioning under sport-specific demands

TABLE A: Conceptual model illustrating the progression of rehabilitation across four phases following nonoperative ACL injury management. Neuromuscular control is emphasised from the early phase and maintained throughout, while strength, plyometric loading, running, and sport-specific demands are progressively increased based on functional criteria.

Abbreviations: COD = Change of Direction; ROM = Range of Motion

Note: Content reflects functional rehabilitation domains and progression characteristics derived from the original training process. Specific exercises and loading parameters are intentionally not disclosed.