# NEUROPLASTIC MULTIMODAL ACL REHABILITATION

## INTEGRATING MOTOR LEARNING, VIRTUAL REALITY, AND NEUROCOGNITION INTO CLINICAL PRACTICE

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INTRODUCTION

Non-contact rupture of the anterior cruciate ligament (ACL) is a common sports-related injury typically warranting extensive rehabilitation and\or surgical intervnetion[1–5]. Athletes that return to full participation are at an elevated risk for re-injury or injury to the contralateral limb with an estimated 1 in 4 athletes sustaining a second injury after returning to high-level sport[1,6]. The high re-injury rate among athletes has been a focus for researchers attempting to identify modifiable risk factors for rehabilitation techniques to improve return-to-sport (RTS) outcomes. Traditional rehabilitation after ACL injury has focused on both 1) time-based, knee-specific exercises, and 2) isolated physical abilities (e.g., muscle strength, hop distance) for RTS readiness[7]. Recently, a multifactorial approach to rehabilitation (in which exercises incorporate the sensorimotor spectrum, are multi-segmental, and combine the person, task, and environment in a dynamic systems approach) has received attention as a means to improve motor coordination and decrease re-injury risk[6,8].

Orthopedic rehabilitation must move beyond the traditional emphasis on mechanics and muscle strength and consider nuanced sensorimotor control deficits to ensure complete recovery and readiness for RTS. ACL injuries during sport are predominantly non-contact, suggesting injury may be a product of sensorimotor errors that result in a neuromuscular control strategy unable to accommodate deleterious joint loading[6,9,10]. Further, the vast majority of non-contact injury events occur while athletes are cognitively distracted, attending to complex visual demands or environmental stimuli[9,11,12], suggesting that neural mechanisms may directly contribute to the athlete's ability to safely interact with the dynamic sport environment[13,14].

Rehabilitation efforts that incorporate multimodal aspects of motor learning and neurocognition may improve functional outcomes for ACL reconstruction (ACLR) patients. These modalities include training with an external focus of attention, implicit feedback, differential learning, novel sensory reweighting, and virtual reality technologies. Below we introduce several key concepts regarding motor learning principles, neurocognition, and new technologies that clinicians may incorporate into modern rehabilitation practice. In addition, we outline a theoretical ACLR rehabilitation program that incorporates these concepts and gives clinicians an immediate practical application.

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**Figure 1:** Strobe glasses rapidly cycling OFF (left) and ON (right) to knockdown visual feedback.

2

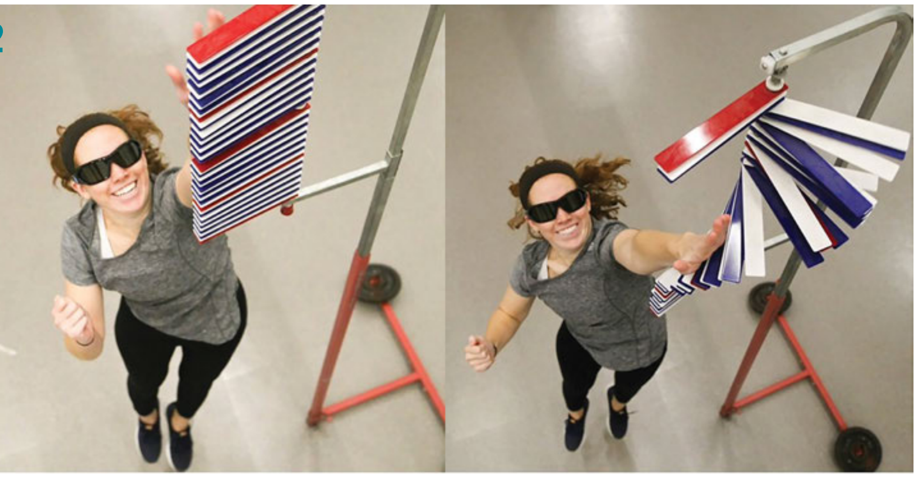

**Figure 2:** Strobe glasses used during a jump task to facilitate sensory reweighting from visual dependence to increased proprioception reliance.

## WHY DO WE NEED TO CONSIDER MOTOR LEARNING PRINCIPLES IN REHABILITATION?

Motor learning is a term that corresponds to the relatively permanent acquisition and refinement of motor skills[15]. The principles underlying motor learning incorporate fundamentals of neuroscience, psychology, and rehabilitation science to explain how motor development and re-learning occurs after injury. The use of motor learning principles can improve rehabilitation outcomes and be implemented with a variety of clinical populations such as stroke, amputee and motor speech disorders[16,17]. Traditional musculoskeletal rehabilitation approaches tend not to integrate motor learning principles explicitly or with a goal to induce neuroplasticity, or sensory reweighting, or virtual reality technologies that support optimized functional performance and recovery. Incorporation of these new technologies and therapies may provide a means to reduce the high reinjury rate after ACLR, as the ACL injury event is essentially a coordination error in sensory, visual or motor processing[18,19]. Furthermore, emerging evidence has demonstrated the existence of central nervous system changes following acute traumatic knee injuries, which may influence motor control and functional outcomes of ACLR patients[20–22]. As such, motor learning strategies, and other modalities, may constitute a potential solution to mitigate neuroplastic effects of injury that can impede rehabilitative progress[23].

## KEY MOTOR LEARNING PRINCIPLES TO AUGMENT REHABILITATION

Effective rehabilitation prepares an athlete for return to play through the transfer of clinically learned motor skills to the athletic environment and modifications to exercise prescription that optimize learning may facilitate beneficial neuroplasticity[23]. As discussed in the article by Gokeler and Benjaminse in this special edition (see pages 62-65) it is recommended that athletes transition to **an external focus of attention** movement strategy as soon as possible to enhance attentional processing during movement performance, freeing up cognitive processing[24–26]. Similarly, rehabilitation that imparts **implicit learning**, rather than offering explicit directions, may reduce the cognitive demand on athletes to successfully perform safe movements[27–30]. New biofeedback technologies also hold promise to induce implicit learning that is tailored to reduce multi-variable injury-risk factors[31–33].

Differential learning encourages athletes to readily adapt their movement strategies to perform a task under constantly changing parameters[34]. These include changing the technique of a task, the environment where the task is performed, and the duration or intensity. The main goal for differential learning is to modify how the task is performed after every 1-3 repetitions to force the athlete to continuously adapt to the variable conditions and promote biomechanical adaptations that are best suited for the individual. This is counter to common training practices that focus on continuous repetition of the "correct" form; however, rarely in competition are there opportunities to perform repetitive "ideal" movements. Thus, clinicians are encouraged to alter task, context and\or environmental constraints to improve learning over time, despite potential reductions in immediate performance[35–37].

## EMERGING TECHNOLOGIES TO ADDRESS SPECIFIC POSTINJURY NEUROPLASTICITY DURING NEUROMUSCULAR TRAINING

Incorporating new technologies into therapy also provides unique avenues to increase the neurocognitive demand placed on athletes during rehab. The use of *stroboscopic glasses* to induce **sensory reweighting** is one such modality[38–41]. Sensory reweighting describes how the central nervous system integrates separate sensory stimuli (e.g., visual, vestibular, proprioceptive) by weighting them according to reliability, essentially decreasing the weight of *unreliable* stimuli and thereby increasing the weight of others[42,43]. Stroboscopic glasses (Figure 1) may facilitate sensory reweighting by allowing clinicians to induce a standardized knockdown to visual feedback that can be progressed in difficulty as their patients recover (Figure 2). This modality may enhance proprioceptive processing, which is damaged after injury, by decreasing the salience of visual feedback for motor control (hence reweighting).

A strength of stroboscopic glasses is they may be used during any therapy or exercise as an adjunct tool since this modality varies the degree of visual feedback without entirely removing an athlete's vision. After verifying that their athletes can complete an exercise with the glasses at the easiest setting (i.e., shortest duration of the opaque state), clinicians may increase the difficulty level (i.e., reducing the amount of visual feedback) by increasing the duration of the opaque state (range: 25 to 900 milliseconds) while the clear state remains constant (100 milliseconds)[41]. Examples of exercises that may be coupled with stroboscopic glasses include agility drills, balance tasks, plyometrics, running, cutting, pivoting, etc. Additionally, clinicians may increase the neurocognitive demand for their athletes by introducing external visual targets/goals (e.g., jumping to hit an overhead target) or dual-tasking (e.g., have the athlete countdown from 100 by 7 while performing a balancing on a single leg) while wearing the stroboscopic glasses.

Virtual reality also brings new potential to induce **contextual interference** (see article by Gokeler and Benjaminse – pages 62-65) and additional visual-spatial and neurocognitive challenges to rehabilitation[44–46]. The advent of virtual reality headsets that utilize a typical smartphone display has reduced upfront costs, allowing this technology to become broadly available[44]. Promising uses include augmenting typical rehabilitation "downtime" such as during passive modalities like cryotherapy or electrical stimulation to allow **mental practice**[47] with visual immersion on a virtual field of play. As therapy becomes more demanding, more advanced exercises can implement visual-vestibular perturbations through observing moving environments (e.g. riding a roller coaster) for postural control training. For further examples of how virtual reality can be integrated within rehabilitation see the article in this special edition by Bonnette et al (pages 72-77 ).

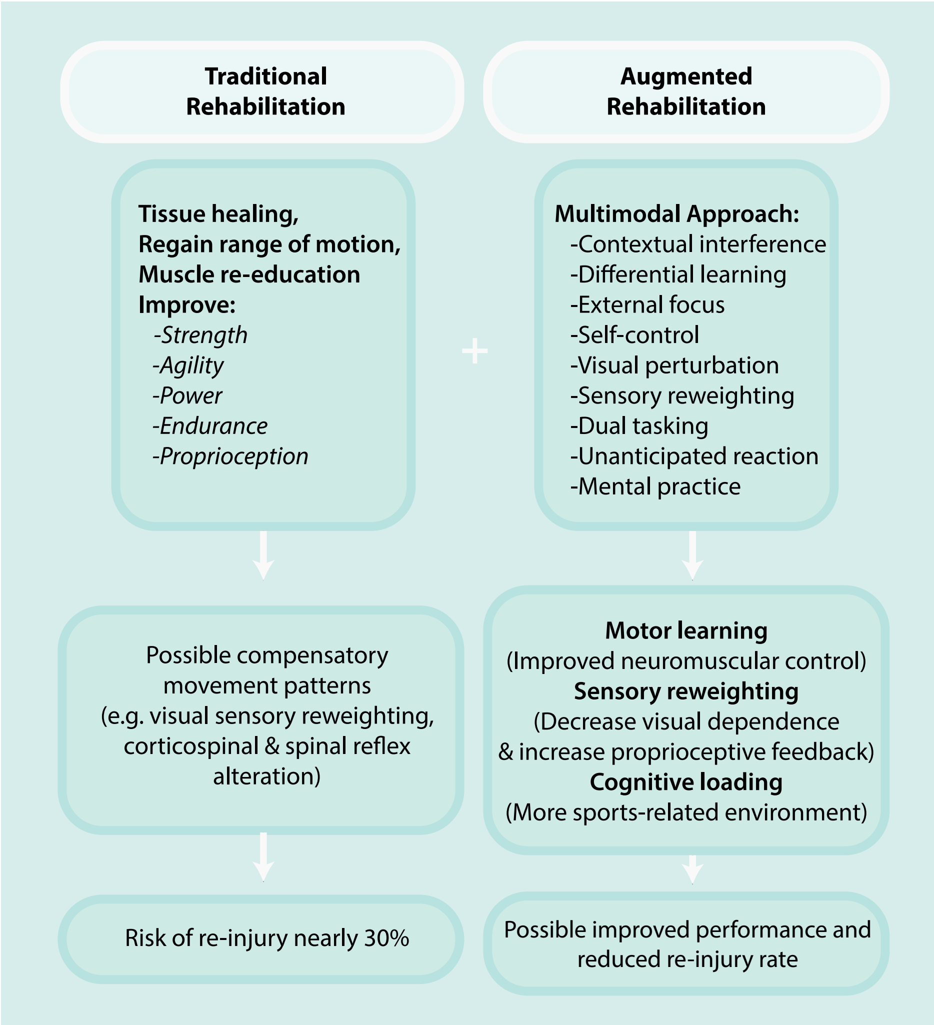


**Figure 3:** Multimodal rehabilitation builds on the traditional rehabilitation model by incorporating motor learning and neurocognition into clinical practice. The integration of these principles is not time specific or tool dependent. Instead it is highly customizable to the goals of the patient and practitioner.

## PRACTICAL APPLICATION

To incorporate these novel aspects of multimodal rehabilitation, we have outlined a theoretical case study below to give clinicians an example on how to augment their current therapy with the tools and methods outlined in this article. The case study is divided into four generalizable phases of rehabilitation progression (early, mid, late, and return). We advocate an *augmentative* approach (Figure 3) when incorporating these principles or modalities, they do not replace any exercise or rehabilitative goal, they are to be used as adjuncts during the exercises you are already prescribing. The fundamentals of rehabilitation including range of motion, strength recovery and basic movement pattern restoration are still the primary goals. Multimodal rehabilitation can be implemented using a variety of tools and exercises as outlined earlier in this article.

## THEORETICAL CASE STUDY

**Patient:** 17-year-old female soccer player
**Position:** Goalie
**Exposure:** Starter
**Repair:** Ipsilateral patellar tendon graft
**Mechanism of injury:** Non-contact ACL injury when pivoting to make a save.

### EARLY PHASE

In the early phase of rehabilitation, the main goal is to manage pain and swelling while regaining range of motion (ROM) and quadriceps activation. Clinicians need to be cognizant of prescribed exercise protocols that may vary based on type of surgery, degree of injury or other related factors and therefore limits that may affect ROM and load-bearing exercises for proper allotment of time for tissue healing. See Figure 4 for examples of a novel treatment plan that can be incorporated to complement traditional rehabilitation approaches suitable for this phase in the 'athletes journey'.

## 4 EARLY phase

### Mental Practice
Equipment:
*Virtual Reality Goggles*

Watch immersive soccer game in VR or play VR soccer game for goal keeping while getting treated with cold modality

**Rehab Focus** *Decrease Joint Effusion*

### External Focus
Equipment:
*Blood Pressure Cuff*

Patient supine, blood pressure cuff beneath involved limb, perform knee extension to compress cuff, attempt to reach a target force

**Rehab Focus** *Increase ROM (extension)*

### Contextual Interference
Equipment:
*TV, Computer or Phone*

Numbers randomly appear on the screen:
ODD: Do straight leg Raise
EVEN: Do Quad Set

**Rehab Focus** *Neuromuscular Re-education*

## 5 MID phase

### External Focus
Equipment:
*Laser Pointer*

Perform lunge with laser pointer attached to thigh, aim pointer at target on the floor or trace a target outline on the floor

**Rehab Focus** *Neuromuscular Control*

### Self-Controlled
Equipment:
*Optional- weights*

Squat: allow athlete to take control of the treatment ONLY providing feedback when requested

**Rehab Focus** *ROM & Strength*

### Visual Perturbation
Equipment:
*Virtual Reality Goggles*

Use Virtual Reality to add perturbation to a balance task, stand on single leg while watching an Immersive Roller Coaster Video

**Rehab Focus** *Balance Training*

## 6 LATE phase

### Unanticipated Reaction
Equipment:
*FITLIGHT*

Use 6 Meter Hop Test method for training

**Rehab Focus** *Reaction time & Focus of Attention*

### Sensory Reweighting
Equipment:
*Strobe Glasses*

Perform ball passing, single leg stance, alternating feet with Strobe Glasses

**Rehab Focus** *Focus of Attention*

### Dual Task
Equipment:
*TV, Computer or Phone*

Patient Jumps off ground, then a TV prompt shows a math problem, solve to determine landing leg

3+4 =7

**Odd-** land on **LEFT**
**Even-** land on **RIGHT**

**Rehab Focus** *Cognitive loading*

## 7 RETURN phase

### Differential Learning
Equipment: *Ball*

Clinician varies throwing of ball to patient, patient varies blocking style (catch, punch single hand/two hand, dive, kick, trap, header)

**Rehab Focus** *Strength / Agility*

### Dual Task
Equipment:
*FITLIGHT*

Lights at periphery, touch "blue" light ONLY, Lights randomly cycle after each touch, perform ball toss with clinician as quickly and accurately as possible

**Rehab Focus** *Cognitive loading*

### Unanticipated Reaction
Equipment: *Ball, 2 people*

Ball shot on goal, patient makes save, quickly stand and prepare to pass, clinician calls out 2 digit number, 21 1st number determines **where** to pass, 2nd number determines **kick** or **throw**.

**Rehab Focus** *Cognitive loading*

**Figures 4-7**

**Rehabilitation must move beyond the traditional emphasis on mechanics and muscle strength and consider nuanced sensorimotor control deficits to ensure complete recovery and readiness for RTS. Incorporating multimodal aspects of motor learning and neurocognition may improve functional outcomes after ACL reconstruction.**

MID PHASE

During the Mid Phase of rehabilitation, typically between 3-6 weeks post-surgery, the main goals for patient progression are retention of full ROM while continuing to improve strength. Typically, proprioceptive exercises to improve balance and kinesthetic awareness are worked into treatment as tolerated. See Figure 5 for three tasks that can be implemented to further incorporate an augmentative approach during rehabilitation suitable at this phase.

LATE PHASE

The Late Phase of rehabilitation refers to a time point typically between 6 to 12 weeks post-surgery. Following the traditional rehabilitation model, the main goals are to achieve full ROM with quadriceps strength greater than 80% of the contralateral limb, increase the difficulty of proprioceptive exercises and begin to implement agility and power tasks into treatment. This is an excellent time to integrate dual task, unanticipated reactions and sensory reweighting exercises that will challenge the patient to reduce their reliance on visual feedback and potentially rewire the brain to interpret proprioceptive feedback during increasingly complex tasks. See Figure 6 for several examples.

RETURN PHASE

There are many factors that must be assessed during the RTS decision or Return Phase. It is important to follow protocols that are best suited for each patient and supported in the literature. The implementation of multimodal treatment tasks is not intended to replace functional assessment but can be incorporated during the end stages of rehabilitation or as an add-on to a patient exercise routine after returning to full activity and cleared by a physician. In this phase, patients will focus on sport-specific exercises that are intended to be extremely challenging both physically and cognitively while performed in a controlled environment. All of the previously mentioned multimodal tasks can be implemented with a major focus on motor learning, cognitive loading and sensory reweighting that are real-to-sport and require quick decision making from unanticipated events. See Figure 7 for several novel examples.

CONCLUSION & FUTURE CONSIDERATIONS

With recent evidence in support of neural contributions to ACL injury[48] and rate of recovery, rehabilitation protocols may benefit from incorporation of approaches that target the sensorimotor system. The integration of motor learning principles (external focus and differential learning) and/or new technologies (virtual reality, FITLIGHT, stroboscopic glasses) may bolster current ACL rehabilitation protocols and improve patient recovery. Additionally, other recent investigations have also highlighted perioperative considerations that may impact ACL patient outcomes and readiness for RTS. These may include, but are not limited to, anesthesia alternatives[49] and advances in surgical approach[50]. Furthermore, other factors, such as psychological distress, kinesiophobia or fear of reinjury, have been implicated as an important determinant for not returning to sport.[51] Therefore, future protocols may warrant the incorporation of psychological readiness considerations within RTS criteria.

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