Review Article

A clinical practice review of therapeutic movement-based anterior cruciate ligament reconstruction return to sports bridge program: the biological, biomechanical and behavioral rationale

John Nyland[1,2]^, Brandon Pyle[3], Jarod Richards[2], Kei Yoshida[3], Jennifer Brey[1,2], Sam Carter[1,2]

[1]Norton Orthopedic Institute, Louisville, KY, USA; [2]Department of Orthopaedic Surgery, University of Louisville, Louisville, KY, USA; [3]MSAT Program, Spalding University, Louisville, KY, USA

Contributions: (I) Conception and design: J Nyland; (II) Administrative support: J Nyland; (III) Provision of study materials or patients: J Nyland, B Pyle, J Brey, S Carter; (IV) Collection and assembly of data: J Nyland, B Pyle; (V) Data analysis and interpretation: J Nyland; (VI) Manuscript writing: All authors; (VII) Final approval of manuscript: All authors.

Correspondence to: John Nyland, EdD, ATC, DPT, SCS, CSCS, FACSM. Norton Orthopedic Institute, Louisville, KY, USA; Department of Orthopaedic Surgery, University of Louisville, 550 S. Jackson St., 1st Floor ACB, Louisville, KY 40202, USA. Email: john.nyland@louisville.edu.

Abstract: This clinical practice review describes the biological, biomechanical and behavioral rationale behind a return to sport bridge program used predominantly with non-elite, youth and adolescent high school and college athletes following anterior cruciate ligament (ACL) reconstruction. Post-physiotherapy, this program has produced outcomes that meet or exceed previous reports. With consideration for athletic identity and the Specific Adaptations to Imposed Demands (SAID) principle, the early program focus was on restoring non-impaired bilateral lower extremity joint mobility and bi-articular musculotendinous extensibility. Building on this foundation, movement training education, fundamental bilateral lower extremity strength and power, and motor learning was emphasized with use of external focus cues and ecological dynamics—social cognition considerations. Plyometric and agility tasks were integrated to enhance fast twitch muscle fiber recruitment, anaerobic metabolic energy system function, and fatigue resistance. The ultimate goal was to achieve the lower extremity neuromuscular control and activation responsiveness needed for bilateral dynamic knee joint stability. The rationale and conceptual basis of selected movement tasks and general philosophy of care concepts are described and discussed in detail. Based on the previously reported efficacy of this movement-based therapeutic exercise program we recommend that supplemental programs such as this become standard practice following release from post-surgical physiotherapy and before return to sports decision-making.

Keywords: Anterior cruciate ligament (ACL); neuromuscular control; outcome study; motor learning; dynamic knee stability

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Introduction

Reports have questioned the ability of standard post-surgical physiotherapy to adequately prepare patients for safe, unrestricted return to sports following anterior cruciate ligament (ACL) reconstruction (1,2). Prolonged recovery time needs (3) and practice constraints related to limited insurance coverage can make it difficult to provide needed care, particularly during the late recovery period. According to the World Health Organization's International Classification of Functioning, Disability and Health (ICF) (4), recovery post-injury and surgery should not solely

^ ORCID: 0000-0001-9033-5020.

focus on the disorder or disease, but should also consider any other physiological and psychological impairments, function or activity restrictions, and participation restrictions with more holistic considerations of personal and environmental contextual factors.

Most non-contact ACL injuries occur with the knee flexed <30° in the presence of poorly controlled frontal plane knee and trunk alignment (5-8). Athletes who sustain an ACL injury and undergo reconstructive surgery also possess high second ACL injury rates (9). Among a cohort of healthy young athletes post-ipsilateral ACL reconstruction, the contralateral knee ACL injury rate was greater than the initial ACL injury incidence rate (9). Young athletes who return to pivoting or cutting sports after ACL reconstruction have a 15-fold greater risk for sustaining a primary, contralateral ACL injury than healthy subjects (particularly females) (9). After ACL reconstruction, approximately one in three athletes ≤20 years of age experience a second ACL injury, with ACL graft re-injury and contralateral ACL injuries showing similar incidences (10).

Rationale and knowledge gap

To achieve success, return to sports criteria should display significant reductions in the rate of a second injury to the surgical knee and reduced incidence of primary ACL injury at the contralateral knee. An important biomechanical factor related to increased second knee injury risk is asymmetrical loading with increased loads occurring at the contralateral side (11,12). Too often, ACL reconstruction rehabilitation focuses solely on surgical limb impairments, neglecting the opportunity to correct modifiable risk factors that might prevent ACL reconstructed knee re-injury and primary ACL injury at the contralateral knee. Many ACL injuries occur between 19 and 23 years of age; however, females often experience them earlier, between 14 and 18 years of age (13,14). Athletic individuals who remain active after they reach 25 years of age are less likely to sustain another injury to their ACL reconstructed knee, or primary injury to their contralateral knee (15,16). Therefore, a goal of any knee injury or re-injury prevention program should be to enable athletes to remain knee injury-free at least until they are past 25 years of age. Previous reports have suggested therapeutic exercise program training interventions based on literature reviews (17-19). The recommendations provided in this clinical practice review are based on the evidence-based program that we have previously reported (2).

Objective

This clinical practice review discusses the biological, biomechanical, and behavioral rationale behind a prospective cohort (level II evidence) return to sports bridge program that has been successfully used to treat non-elite, youth and adolescent high school and college athletes following ACL reconstruction with excellent clinical outcomes (2).

Return to sports bridge program and current outcomes

An 8-session evidence-based program was implemented after physiotherapy among a group of 150, predominantly non-elite, youth and adolescent high school and college athletes (83 males) of 20.3±7.2 years of age at 7.1±2.5 months post-ACL reconstruction (2). *Session 1* focused on learning quality athletic movements that incorporated whole body long-axis rotation and bi-articular lower extremity musculotendinous extensibility to restore normal knee joint mobility during slow speed tasks. Using a weighted vest, *Session 2* added approximately 10–20% bodyweight resistance to the movements learned during Session 1. During *Sessions 3* and *4*, two-legged and one-legged hopping tasks were added, respectively. During *Session 5*, multi-directional agility tasks were added. *Sessions 6-8* focused on any recalcitrant impairments or activity limitations, confirming dynamic knee joint mobility and stability in positions of function, load tolerance, physiological or emotional resilience or fatigue resistance prior to functional testing. Important program activities/tasks and the rationale behind their use are described in *Table 1*. To better accommodate healing tissue recovery/remodeling and motor learning while providing sufficient time for the athlete to reflect about their injury and continued sport performance, a twice weekly training format was followed. Once a week, a rehabilitation clinician guided a 2-hour duration session focusing on lower extremity stretching, functional movements that combined trunk and lower extremity neuromuscular control, strength/power, sprint and agility training with sport-specific task performance and monitored rest periods (20-22). Once weekly independent sessions were also performed consisting of six sets of progressive resistance bilateral single leg presses (12, 12, 10, 10, 8, 8 repetition progression), three sets of 15 repetition single leg lateral step-ups on a 10.1–15.2 cm tall step (one set performed with eyes closed), and three sets of 15 repetition lateral scissor planks. The initial single leg press goal was 8 repetitions with each side using bodyweight

Table 1 General movement-based activity/task categories, specific activity/tasks, session(s) of performance, activity/task goal, primary movement planes, performance condition or cue, and volume

Category	Activity/task	Sessions	Goal	Primary movement plane			Condition/cue	Volume
				Sagittal	Frontal	Transverse		
Stretches	Contract-relax hip extension (*Figure 1A*)	1–8	Improve hamstring extensibility, assess hip extensor strength	√			Supine, extend hip with maximal effort with no sudden jerk	3, 10 sec contractions, 20 sec stretches
	Prone-to-sidelying hip extension-knee flexion stretch (*Figure 1B*)	1–8	Improve hip flexor, knee extensor extensibility	√	√		Prone-to-side lying, bring heel to butt as the rehabilitation clinician adducts the hip to stretch pelvic deltoid muscles	3, 30 sec reps
	Crossed knee to chest stretch (*Figure 1C*)	1–8	Improve gluteal muscle, tensor fascia latae, iliotibial band, lower back extensibility	√	√	√	Supine, bring knee toward opposite shoulder	3, 30 sec reps
Dynamic warm-up	Quadruped “Bird Dog” (*Figure 2*)	1–8	Improve dynamic hip and trunk control and stability	√	√		Alternating arm-leg lift with 0.5–1 kg weight in each hand, flat back, knees at shoulders width apart	1 set, 20 reps, 2 sec hold
	“Bounce back” diagonal lunge (*Figure 3A*)	1–8	Smooth, symmetrical hip-knee-ankle sagittal plane movements	√			Move forward with ball overhead, eyes open, progress to eyes closed; low profile or no shoes	15 m ×2
	Lateral shuffle (*Figure 3B*)	1–8	Smooth, symmetrical hip-knee-ankle (subtalar joint) shared, frontal plane movements		√		Move sideways with ball at chest, progress to eyes closed; low profile or no shoes	15 m ×2
	Form run simulation (*Figure 3C*)	1–8	Smooth, symmetrical non-impact long-axis rotation with multi-planar trunk and lower extremity movements	√	√	√	Move forward, twist opposite elbow toward knee and finish on toes, progress to eyes closed; low profile or no shoes	15 m ×2
	Back step—butt kick (*Figure 3D*)	1–8	Smooth, symmetrical increases in hip flexor/knee extensor extensibility, and knee flexor strength	√			Move backward while looking up with hands behind head. After extending hip, flex knee bringing heel-to-butt; low profile or no shoes	15 m ×2
Foundational NMC movement	Ball-to-wall (*Figure 4A,4B*)	1–8	Improve dynamic frontal-transverse plane trunk and lower extremity NMC and stability		√	√	While standing on a stability pad with the knee flexed 20°–30° holding a ball out front, perform alternating, slow speed side-to-side long-axis rotational movements	2 sets, 15 reps
	Karate kid (*Figure 4C*)	1–8	Improve dynamic frontal plane trunk and lower extremity NMC and stability	√	√		While standing on a stability pad with knee flexed 20°–30° holding a ball overhead perform alternating, slow speed knee-to-chest movements	2 sets, 15 reps
	Athletic ready position (*Figure 5*)	3–8	Balanced symmetrical posture to be replicated during all hopping, jumping and directional change movement tasks	√	√	√	With symmetrical semi-flexed hips-knees-dorsiflexed ankles the athlete assumes a safe landing posture approximately 80% of the time when performing hop, jump, directional change tasks	80% proficiency
Foundational strength movements	Single leg press (*Figure 6A*)	2–8	Restore foundational pre-morbid composite lower extremity extensor strength	√			12/12/10/10/8/8 reps/set, initially with bodyweight resistance for 8 rep maximum goal. As needed supplement with 2 additional 8 rep 2-to-1 leg negative sets	6 sets
	Seated knee extension with hip adduction (*Figure 6B*)	2–8	Restore foundational pre-morbid quadriceps femoris activation	√			20 reps without distal tibial loading. Full knee ROM in seated position. Maximal effort hip adduction while extending and flexing bilateral knees	1–2 sets of 20 reps
	Single leg lateral step-ups (*Figure 7*)	1–8	Improve trunk and composite lower extremity extensor strength	√	√		While standing on a 0–12 inch tall surface, holding a ball overhead with stance foot angled 10° outward, perform step-ups keeping the patella aligned with point of shoe or 2nd toe. Progress to eyes closed	2 sets, 15 reps
	Lateral scissor planks (*Figure 8*)	1–8	Improve hip abductor-external rotator-extensor and trunk strength		√		Bridge up, keep pelvis slightly inward while abducting-externally rotating-extending the top hip	2 sets, 15 reps
	Squats on Bosu® ball with 3 quick side-to-side taps (*Figure 9*)	1–8	Improve dynamic sagittal plane trunk and lower extremity control and stability	√	√		With ball held overhead, perform a slow squat with 3 quick side taps at the bottom. Try to maintain a level surface, progress to eyes closed; low profile or no shoes	50 reps (25 with eyes closed)
Foundational NMC movement	Matrix (*Figure 10*)	3–8	Improve dynamic multi-planar trunk and lower extremity control and stability	√	√	√	From the athletic ready position, progressing to a 4–6 inch step, perform forward, lateral and backward stepping with long axis rotation	3 sets, 3 mins each with metronome cues
	Long-axis-rotational medicine ball toss (*Figure 11A-11C*)	4–8	Whole-body long axis rotational movement to improve upper extremity-trunk-lower extremity coordination while maintaining 20°–30° knee flexion		√	√	Holding a medicine ball out front, cock, accelerate, and explode as you release the ball to “knock down the wall”	2 sets, 15 reps

Table 1 (*continued*)

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Category	Activity/task	Sessions	Goal	Primary movement plane			Condition/cue	Volume
				Sagittal	Frontal	Transverse		
Agility	Single leg lateral step-overs (*Figure 12*)	1–4	Improve single leg standing balance, trunk and lower extremity control and stability	√	√		Progressive stepping over variable height caution tape. Maintain single leg stance with 20°–30° knee flexion for 2–3 sec Perform with eyes open, closed	15 m ×2 reps
	Circuit (*Figure 13A*)	4–8	Improve agility, anerobic endurance, willingness to single leg load	√	√	√	Side-to-side repetitive running directional change (cutting) task	2–3 reps of approximately 30–60 sec duration
	Mirror reaction drill (*Figure 13B*)	5–8	Improve explosive directional change reactions, anerobic endurance	√	√	√	Explosive movement reaction time task alternating between offense and defense	10 reps of approximately 3–5 sec duration
	5–15 m shuttle run (*Figure 13C*)	4–8	Improve agility, anerobic endurance, resilience	√			Forward sprints to deliver a series of 7–10, 0.5 kg balls to a bin (20–70 sec target time depending on task distance)	2–3 reps of approximately 20–85 sec duration
	Short-ball-tall (*Figure 13D*)	5–8	Improve agility, anerobic endurance, willingness to get up from and down to the floor quickly	√	√	√	Cued movement from supine or prone on the floor to sequential objects (ball-tall-short, in random order)	2–3 reps of 30 sec duration
Plyometrics	Speed skaters (*Figure 14A-14C*)	3–8	Improve single leg dynamic knee stability	√	√		A single leg hop triplet of right-left-right or left-right-left (then stabilize for 2–3 sec) repeats. With lacrosse stick in hand this movement provides a useful method for evaluating repetitive single leg loading characteristics	20 m ×2 reps
	Bounding (*Figure 15A*)	4–8	Improve lower extremity power, control and stability; reduce fear, increase self-efficacy	√	√		Progressive alternating side continuous hopping trying to maximize vertical displacement and land using a controlled, bilaterally symmetrical landing technique	20-30 m ×2 reps
	Kangaroo jumps (*Figure 15B*)	3–8	Improve lower extremity power, control and stability; reduce fear, increase self-efficacy	√	√		Progressive, continuous vertical jumps for height with controlled landings with knee at 20°–30° flexion. 2 leg-to-1 leg progression. Perform with eyes open, closed	15 m ×2 reps
	Double-to-single leg jumps (*Figure 15C*)	3–8	Improve lower extremity power, control and stability; reduce fear, increase self-efficacy	√	√		Progressive jumping over variable height caution tape with controlled single leg landings with knee at 20°–30° flexion. Perform with eyes open, closed	15 m ×2 reps
	Frog jumps (*Figure 15D*)	3–8	Improve lower extremity power, control and stability; reduce fear, increase self-efficacy	√			Progressive, sequential 2 leg horizontal jumps for distance. Perform with eyes open, closed	15 m ×2 reps

NMC, neuromuscular control; sec, seconds; reps, repetitions.

resistance levels, however, because of frequent surgical lower extremity weakness at program initiation, many athletes had to begin with only 50–75% of the resistance that could be used at the contralateral lower extremity. Single leg press performance (within knee joint "pain-free" limits) was recorded, with a progressively increasing resistance goal at each session. Progressive return to running was started during *Session 3*, initially for 2 miles at ≤20 min (within knee pain-free limits), prior to advancing to 20–40–60 m straight ahead sprints for three repetitions each at 50%, 75%, and 100% intensity levels. Straight-ahead sprints transitioned to zig-zag sprinting over the same distances during Session 6. After completing this 8-week duration program, athletes underwent post-program functional testing.

Athlete reported perceived knee function was measured using the Knee Outcome Survey-Sports Activity Scale (KOS-SAS) at program entry (global score) and completion (global and calculated scores) (23,24). At program completion, athletes completed an additional KOS-SAS survey with both global and calculated scores about their current perception of surgical knee sports function capability readiness when they initiated the program. Self-efficacy, kinesiophobia, fear of re-injury, or health locus of control surveys were also used on a case-by-case, as needed supplemental basis (25-28). Prior to release to unrestricted sports, athletes completed an evaluation consisting of evidence-based objective and subjective criteria. Post-program evaluations were performed with the athlete on their primary sport playing surface while wearing the appropriate shoe. Test sessions were approximately 2 hours duration (range =90–130 min) with five task categories: (I) functional movement form; (II) dynamic knee stability; (III) lower extremity power; (IV) agility; and (V) repetitive sports skills. Movement education focused on improving multi-planar lower extremity biarticular (myofascial, hip and knee flexor, ankle plantar flexor) muscle extensibility during slow speed movements with exaggerated long-axis trunk rotation (2,7,29). Dynamic knee stability tasks included single leg triple hop for distance, and single leg timed hop, and single leg timed crossover hop symmetry tests performed over a 20-m distance. Lower extremity power tasks performed over a 20-m distance consisted of bounding, two-legged horizontal "frog" hops for distance, and two-legged-to-single-legged "kangaroo" hops with a qualitative assessment of vertical jump amplitude, and soft landings with accentuated knee flexion. Agility tasks included the National Football League (NFL) "L" and 5–10–5 running directional change drills and a cued, triangle pattern "short-tall-ball" task (2,29,30). Repetitive sport skills represented 2–4 fundamental tasks deemed essential to the athlete's performance by the athlete and the rehabilitation clinician. Test criterion achievement was represented by successful completion of the subjective KOS-SAS (>85%), objective hop tests [≥90% limb symmetry index (LSI) on at least 2 of 3 hop tests, and ≥90% LSI during eight repetition maximum single leg press performance]. To pass the test criteria athletes also had to have no signs of limb favoring or knee effusion during any sport movement task. Upon passing test criteria, athletes were released to unrestricted sports practice. After 2 weeks of unrestricted practice with no complaints, the athlete and the team medical and coaching staffs shared decision-making about when they were ready to safely return to competition. All athletes were released to practice with 5–6 neuromuscular strength or control maintenance homework activities/tasks and static stretches that they continued independently or with team medical staff oversight.

Of 150 athletes who had successfully completed the program and returned back to sports by 9.1±2.5 months post-surgery, ten sustained a new knee injury (6.7%) by 6.8±3.2 (mean ± standard deviation) years (range =2–13 years) post-surgery (2). To date this program has resulted in 1.3% ipsilateral non-contact knee re-injury and 2.7% non-contact contralateral knee injury rates. This result is lower than knee re-injury rates cited in several previous level I and level II evidence reports (31-33). These favorable outcomes were also achieved with most athletes perceiving comparable or better sport performance restoration compared to their pre-injury level (2).

Philosophy of care

An ACL injury generally contributes to mechanical knee instability with altered joint proprioception, kinesthesia, and impaired neuromuscular control of dynamic knee stability. Impaired somatosensory system input requires the athlete to increase visual feedback reliance with increased higher level cortical function dependence to regulate motor control (34). Increased higher level cortical brain activation for postural control purposes negatively affects performance, increasing movement deficits more in athletes post-ACL reconstruction than in healthy individuals (35). These deficits are more noticeable when reactive movements are attempted with more frequently flawed lower extremity biomechanics and altered knee loads compared to planned movement performance (36). Thus, re-training reactive neuromuscular activation and dynamic knee stability as well as confirming movement quality during tasks requiring reactive performance are essential return to sports training components (1). We now better appreciate that ACL injury represents a neurophysiological phenomenon with neurocognitive and sensorimotor control impairments that remain after ACL reconstruction and rehabilitation (21,37).

This return to sport bridge program took place in a gym or outdoor environment that stimulated motor control and learning, general and sport-specific movement task self-efficacy development with consideration for biological, biomechanical and behavioral healing timeframes, increased load tolerance, fatigue resistance, and overall performance resilience. Within this environment, in addition to their physical recovery, recovering athletes performed both individual and small group activities using social cognitive theory principles to guide them through cognitive appraisals, emotional and behavioral responses (38). A commonly used rehabilitation axiom is that proximal stability enhances distal mobility. This suggests that trunk and lumbopelvic region postural stability can enhance more peripheral joint function. However, dynamic trunk and lumbopelvic region stability can also enhance dynamic knee stability to help prevent injury and improve athletic performance (39). With the knee located between the long femur and tibia levers, it is essential to develop dynamic knee joint control stability through the entire lower extremity.

Athletic identity

Athletic identity is the degree to which an individual identifies with the athlete role, looking to others for acknowledgment of that role with two contrasting forms of passion (harmonious or obsessive) (40). Athletic identity is of particular concern to many youth and adolescent athletes. Athletes with harmonious passion strongly identify with the athlete role, but also develop other life interests. In contrast, athletes with an obsessive sport passion who focus exclusively on their sport to the loss of other life activities, have stronger negative emotions when they are prevented from participation. By young adulthood (≥25 years of age), healthy athletes have developed multi-faceted, more complex self-identities. When they define their identity solely as an athlete, however, this process gets repressed (40). Youth and adolescent athletes with more developed self-identities can better manage sport and life stresses, and will be better prepared to mediate current and future successes and failures (40,41). Rehabilitation clinicians who work with youth and adolescent athletes should remember that physical changes during puberty occur during early (10–13 years) and mid- (14–16 years) adolescence, while late adolescence is dominated by dramatic cognitive, psychosocial and behavioral development (38,39). Adolescent development, including structural brain and cognition changes continue across all stages, even into the third decade of life (40-43).

High total training volume and "elite"-like sports training practice in today's society can span all of adolescence. Personal identity develops most during late adolescence (16–19 years of age) as athletes explore new and hopefully, diverse activities. However, when an adolescent athlete places excessive time and energy solely on sports, they do not engage in other exploratory behaviors, which hinders self-identity development, leading to "identity foreclosure" (42). This can be particularly problematic when the athletic experience is abruptly delayed or ended due to injury (42-44). Athletic identity foreclosure naturally happens during late adolescence as the individual experiences a broader range of academic, social, cognitive, motivational or emotional affective events (42-46). Under normal circumstances, athletic identity divestment occurs naturally to help the adolescent maintain a positive self-concept (42). After ACL injury, surgery, and rehabilitation, the dynamic sport identity can undergo complex changes involving personal, situational, cognitive, behavioral, emotional, and recovery outcome variables (45-48). By devaluating the athletic identity, its threat to reduced athletic performance after knee injury is no longer as important to how the individual defines themselves (45). To ease the transition away from competitive sports and minimize self-identity-related adjustment difficulties, Lally (48) reported that college athletes often proactively reduced athletic identity influences over their last year of competition. Over the initial 2 years after ACL reconstruction, Brewer *et al.* (45) found that patients gradually decreased athlete role identification. Interestingly, the greatest decrease occurred 6–12 months after surgery, which is often the key time during rehabilitation when return-to-sport decisions are made (45). Rehabilitation clinicians must help athletes navigate their athletic identities and cognitive injury appraisals, facilitating harmonious passion and multi-dimensional self-identity development (45,48,49).

Foundational program components

Specific Adaptations to Imposed Demands (SAID) principle

The SAID training principle (50) suggests that the

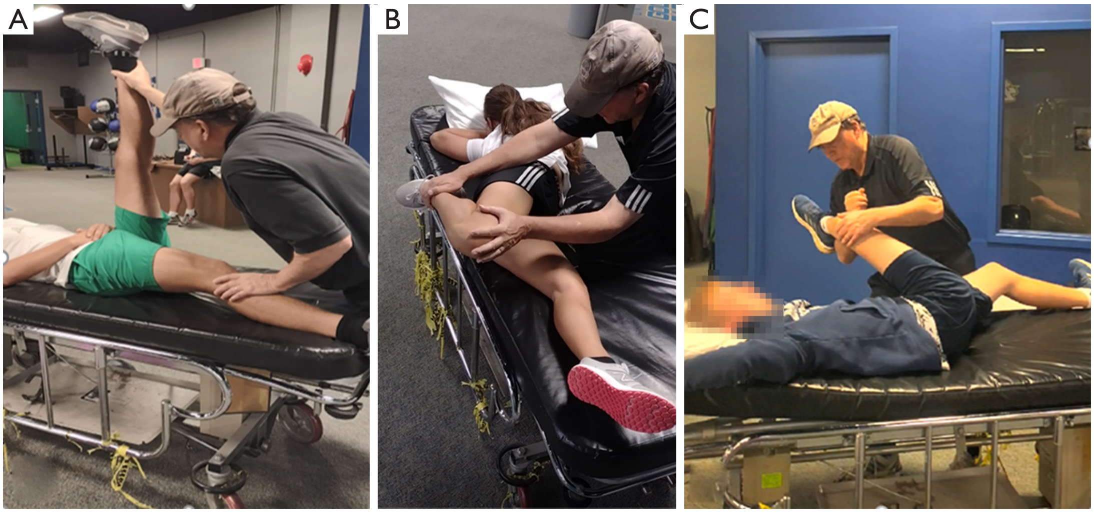

Figure 1 Essential stretches. (A) Contract-relax hamstring stretch to increase myofascial and hamstring musculotendinous extensibility and to evaluate hip extensor strength; (B) prone-to-sidelying hip flexor-knee extensor static stretch to increase myofascial, iliopsoas, and quadriceps femoris musculotendinous tissue extensibility; (C) crossed knee to chest ("piriformis" stretch) to increase myofascial and pelvic deltoid and lower back musculotendinous extensibility. These images are published with the participants' consent.

Figure 2 Quadruped "bird dog" movement to increase composite trunk-upper extremity-lower extremity stability. This image is published with the participant's consent.

specific nature of the neurophysiological and perhaps, psychobehavioral stresses that occur with training drives the adaptations that occur (50,51). Complex dynamic systems must continuously adapt and modify their organizational states. In agreement with the SAID training principle, therapeutic movement-based exercise programs should consider all aspects of training, including, but not limited to the specificity of loading force magnitudes, application points, velocities, variances, impact of sudden unplanned, random or chaotic events, and instructional cues-context in relationship to the time needed for motor plan adaptations, tissue recovery and physiological or psychological homeostasis restoration.

Restoring bilateral lower extremity joint mobility and bi-articular musculotendinous extensibility

An important program component is restoring smooth, symmetrical functional lower extremity joint movements. Joint flexibility and/or musculotendinous and myofascial system extensibility impairments, neuromuscular inhibition, or excessive regional neuromuscular facilitation must be corrected. Having the athlete perform quality multiplanar functional movements at slow speeds makes it easier to identify and correct any segmental kinetic chain impairments that contribute to maladaptive compensations. Particular attention should be given to improving hamstring muscle group (*Figure 1A*), hip flexor and knee extensor (*Figure 1B*), hip external rotator and lower back (*Figure 1C*) extensibility. Foundational to optimizing trunk, lumbopelvic, and hip function is improving long axis trunk rotation and re-establishing hip and knee musculotendinous extensibility, particularly at the thoracolumbar fascia and musculotendinous structures that cross the trunk influencing both upper and lower extremity joint movements and dynamic stability (52) (*Figure 2*).

Movement training education

Functional movement training education provides the athlete with the opportunity to perform non-impact or

Figure 3 Foundational warm-up movements (A) Forward diagonal "bounce back" lunge holding a 6 lb (2.7 kg) medicine ball overhead. Primarily a sagittal plane movement, but adding the diagonal increases the frontal plane movement challenge; (B) lateral slides holding an 8 lb (3.6 kg) medicine ball overhead. Predominantly a frontal plane movement challenge; (C) form run simulation. A forward movement with alternating exaggerated trunk rotation (transverse plane) and hip-knee flexion (sagittal plane), holding the balance point for 2–3 seconds. This movement challenges dynamic trunk-lower extremity dynamic stability during a non-impact, slow velocity movement; (D) back step—butt kick. A backward movement following maximal hip extension with maximal knee flexion, while maintaining trunk extension with the hands behind the head. The task increases hip flexor musculotendinous extensibility and increases high knee flexion hamstring neuromuscular activation. These images are published with the participants' consent.

low impact quality activities/tasks under direct observation and guidance from the rehabilitation clinician. During this process, it is important to welcome movement errors or mistakes such as sudden lateral trunk flexion toward the lead weight-bearing lower extremity or balance loss as essential "teachable moments" for motor learning. The end goal is overall good, but not perfect performance. When perfection is the end goal, the athlete may ignore other useful performance strategies. Re-injury is best prevented when the athlete possesses more than one useful movement strategy. The spine is the primary "engine" that drives locomotion through the lumbopelvic region and upper extremity reaching through the shoulder girdle (53,54). Improving coordinated upper and lower extremity energy transfer and integration through the trunk and lumbopelvic region is vital to knee injury or re-injury prevention and performance (53-55). Therefore, activities to improve lower extremity neuromuscular control and dynamic knee joint stability should integrate trunk, lumbopelvic, and lower extremity function (54-56). Four slow velocity, dynamic movements that should be considered include a forward diagonal lunge holding a medicine ball overhead or at chest level (*Figure 3A*), lateral slides holding a medicine ball overhead or at chest level (*Figure 3B*), form-run simulation (*Figure 3C*) and the back step, butt-kick (*Figure 3D*). These foundational movements performed either barefoot or in low motion control shoes enable both movement quality and dynamic lower extremity musculotendinous and myofascial system extensibility evaluation. Another important movement that develops dynamic knee stability is the "ball to wall twist". During this single-leg (or tandem stance) weight-bearing movement, the knee and hip are maintained in slight flexion as the athlete slowly rotates the trunk and hip from side-to-side (transverse plane emphasis) while holding an object at arm's length away from their torso (*Figure 4A,4B*). The "karate kid" movement brings a knee to the chest (sagittal plane emphasis) during single leg stance while holding a ball overhead (*Figure 4C*). These movements induce temporary frontal plane dynamic knee instability and with isometric quadriceps femoris-hamstring coactivation at approximately 30° knee flexion, facilitates synergistic gluteus maximus, gluteus medius activation to achieve multiplanar dynamic knee stability. The "athletic ready position" of feet approximately shoulder's width apart, hips and knee slightly flexed, and ankles in slight dorsiflexion (*Figure 5*) provides the best common starting and finishing point for translation to sport-specific movements, and for perturbation applications to challenge balance and postural control in either double or single leg stance. Functional movements are performed moving from

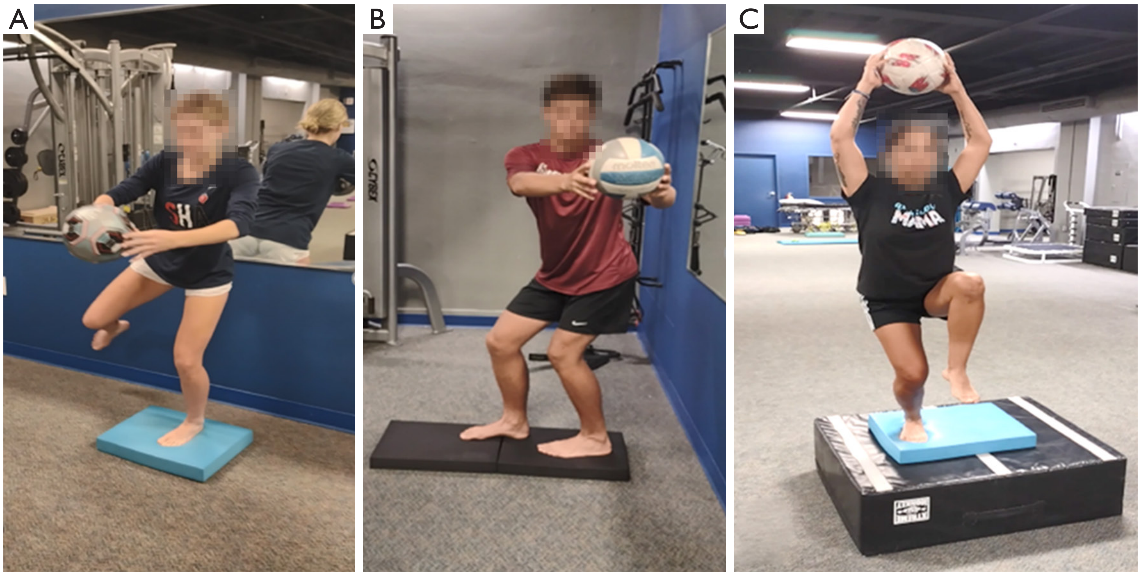

Figure 4 Ball-to-the-wall. Long axis trunk and hip rotation in single leg (A) or tandem (B) stance on a balance pad, while holding a soccer or volleyball away from the body, while maintaining the stance knee at approximately 30° flexion. This movement challenges dynamic frontal and transverse plane knee control. Barefoot on a stability pad and eyes closed further challenges dynamic knee stability during this slow speed movement; (C) Karate kid. Alternating knee to chest movement with the stance leg at approximately 30° knee flexion. This movement also challenges dynamic frontal and transverse plane knee control. Barefoot on a balance pad, eyes closed, and elevation off the ground further increases the dynamic knee stability challenge of this slow speed movement. These images are published with the participants' consent.

Figure 5 Athletic ready position. The routine athletic movement start and finish position with an erect torso, and slightly flexed hips and knees, and dorsiflexed ankles. This image is published with the participant's consent.

smaller amplitude, simpler tasks to larger, more complex tasks with consideration for the total volume and metabolic energy system training needs of the individual athlete. Movement context should possess relevance and validity to the athlete, requiring cognitive engagement, awareness, focus, or mindfulness (56-58). To help them better conceptualize that falls are not fatal, and that they possess the resilience to continue to perform after a fall, prior to functional testing, it is important that they experience several falling or near falling experiences (or reverse falls, quickly getting up from the floor) with rehabilitation clinician guidance and feedback.

Fundamental strength and power

After knee injury and surgery, it is important to restore non-impaired knee and hip extensor strength (*Figures 6-9*). Neuromuscular control training on a foundationally weak musculoskeletal system will result in inadequate adaptations (59). After restoring non-impaired joint mobility and connective tissue extensibility, fundamental strength restoration is essential prior to power training. When a bone-patellar tendon-bone (BPTB) or quadriceps tendon autograft is used, high knee flexion mobility should be restored as the autograft harvest site tends to heal with a stiffer, more scar-like tissue that creates a

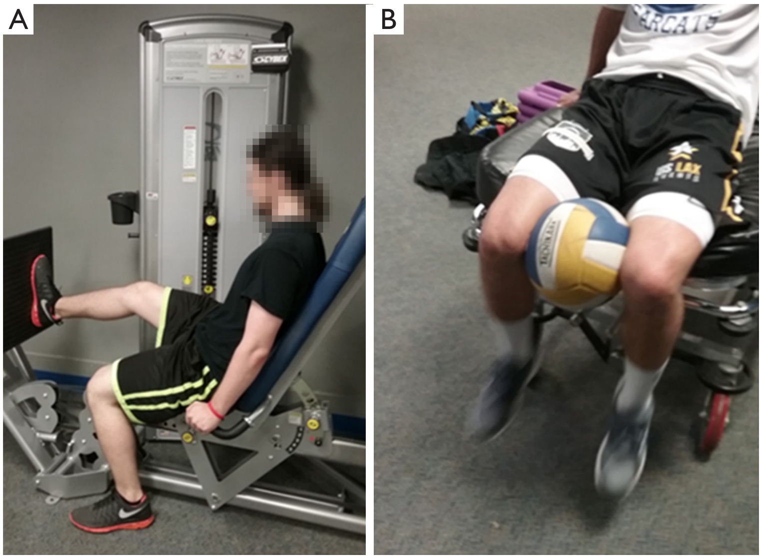

Figure 6 Single leg press (A); bilateral knee extension with hip adduction (B). The single leg press increases closed kinetic chain composite lower extremity extensor moment function. Bilateral knee extension with hip adduction improves more isolated quadriceps femoris activation during an open kinetic chain movement without the distal tibial loads that increase anterior tibiofemoral joint shear forces. These images are published with the participants' consent.

Figure 7 Single leg lateral step up on 12 inch (30.5 cm) step. Holding an 8 lb (3.6 kg) medicine ball overhead, the athlete performs repetitive step-ups keeping the torso erect. Barefoot with eyes closed increases the movement challenge. Maintaining an erect torso increases knee extensor contributions to the composite lower extremity extensor moment. This image is published with the participant's consent.

Figure 8 Single leg lateral scissor plank. Isometric quadriceps femoris and hamstring co-activation with bilateral knee extension. Concentric hip abduction-external rotation-extension at the top lower extremity, isometric hip abduction at the bottom lower extremity. Strengthening of the lateral trunk and hip abductor-external rotators and extensors. This image is published with the participant's consent.

stress riser effect reducing tissue extensibility. When a hamstring autograft is used, it is important to restore high knee flexion and strength following tissue harvest. The rehabilitation clinician needs to consider how differing ACL reconstruction grafts, graft placement locations, tunnel drilling and fixation methods may influence recovery.

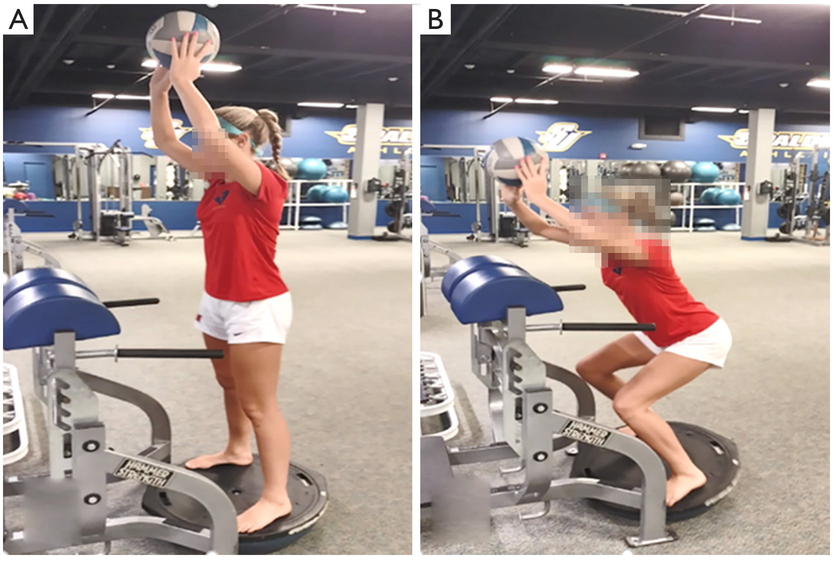

Figure 9 Squats on a Bosu ball (Bosu®, Ashland, Ohio, USA). While holding a volleyball overhead (A) the athlete squats, at the bottom they perform a series of three quick, side-to-side taps (B), actively perturbing the postural control system. Barefoot and eyes closed increases the movement challenge. These images are published with the participant's consent.

Since ACL injuries are associated with impaired ipsilateral hip joint function, to achieve treatment success, it is essential to restore non-impaired hip mobility, correcting impaired tissue extensibility, and restoring hip muscle strength/power. For multiplanar dynamic knee stability to be assured, integrated neuromuscular control must be restored or developed between the trunk, hip, knee and ankle/subtalar joints. Since knee extensor and hip abductor-extensor-external rotator function is often impaired post-ACL injury and surgery, particular focus should be placed on restoring the natural 33% hip, knee and ankle/subtalar joint balanced contributions to multiplanar functional movements. The progressive strength/power restoration continuum of isometric-concentric-eccentric strength/power recovery is important to consider as athletes advance through the program. The negative influences of fast twitch muscle inhibition and muscle fiber atrophy can be mitigated through progressive plyometric activities with attention to balanced hip-knee-ankle/subtalar joint neuromuscular contributions.

Motor learning and plan development

Motor plans are "short cut" brain command pathways that enable highly coordinated, efficient movements. These plans are largely based on past movement experiences, and are not directly dependent on peripheral feedback. This supports the concept that the recovering athlete should perform quality sports movements with rehabilitation clinician guidance. As the athlete is challenged to learn a new movement task, pattern variability naturally occurs. To refine newly learned movement strategies, whenever possible, rehabilitation clinicians should attempt to make better use of the teaching opportunities associated with the athlete's temporary instability or anxiety during specific movement task performance. Although movement path variation temporarily reduces postural stability, with guidance, this process enables the athlete to learn more about their own unique movement system dynamics. To better prevent knee re-injury, athletes should be able to perform essential movements with greater pattern variability while maintaining dynamic joint stability and coordination.

By decreasing coupled hip-knee joint rigidity (60), the neuromuscular control system acquires environmental and task change information. Under controlled conditions, larger movement error magnitude contributes to the athlete developing better movement pattern error detection and correction awareness. The way that an athlete explores and learns new tasks is influenced by the number of potential movement solutions they perceive under their existing set of constraints (61) (*Figure 10*). Rehabilitation clinicians should help them develop greater coordination dynamics adaptability by providing the motor plan access to more than one knee joint injury risk-reducing and performance-enhancing

Figure 10 Matrix. From a 2 to 8 inch (5–20 cm) tall step, in series the athlete slowly steps forward, 45° to the right, 45° to the left, 90° to the right, 90° to the left, 135° to the right, 135° to the left, 180° to the right, 180° to the left and then repeats the sequence for 3 minutes moving at a slow deliberate cadence without sudden acceleration. Barefoot, eyes closed, use of a weighted vest, and a faster cadence increases movement difficulty. This image is published with the participant's consent.

movement pattern solution. Systematic coordination variability, indicative of upcoming instability often underlies motor learning and learning "transfer" between similar tasks (62,63). The ability to translate previous neuromuscular training experiences to new applications has been described as "the savings of learning" (62). With repetitive movement practice, and in response to external perturbations, an athlete's movements become more adaptable, spontaneous, and less rigid (59,63).

There is a paradox between being simultaneously in and out of control during movements (49,51,64). The essence of motor learning is to develop a new, often better motor plan from temporarily reduced stability (49,57,64,65). When movement patterns are stable and predictable, there are no opportunities for the athlete to explore and re-assemble new solutions, therefore motor learning does not occur. New skills are unlikely to be learned when total control exists. Accepting some uncertainty allows room for new skills to be developed and learned. Therapeutic exercise activities/tasks that improve neuromuscular responsiveness, movement skill development, self-efficacy, and resilience for knee injury prevention should challenge the athlete to perform movements during which they perceive themselves to be at the threshold or "edge" of being both somewhat in and out of control, simultaneously stable and unstable, sure and unsure, predictable and unpredictable (49,51,66). Working through this temporary lack of control by developing new movement solutions should initially be experienced during guided rehabilitation and conditioning sessions before athletes are released to unrestricted sports practice.

Motor learning is facilitated when the athlete is cognitively focused, engaged, aware, or "mindful" during sports movement practice. Coyle (58) and Csikszentmihalyi (67) emphasized the need to first slow a movement down, repeat it, and eventually learn to "feel it", becoming "cleverer" or more proficient by overcoming mistakes. The ultimate goal is to improve the athlete's instantaneous neuromuscular control responsiveness, increase confidence and self-efficacy, and decrease kinesiophobia and anxiety. Therapeutic movement-based exercise program success is more likely when the injured athlete perceives themselves to once again be an athlete, not a patient (68). As movement challenges increase, anxiety levels also increase. To stimulate motor learning rehabilitation clinicians must balance the athlete's sense of control, with sufficient anxiety during movement task performance.

External focus of attention, neuroplasticity, and ecological dynamics/social cognition

Guided feedback during knee rehabilitation is typically directed by internal focus of attention cues such as "keep your knees over your toes" or "squat down until your thighs are level with the ground" (69). While an internal focus of attention represents the mental control of specific body parts during movement execution (69), an external focus of attention represents the mental control of movement effects or outcomes outside of the body, such as to "imagine kicking a ball" to increase knee extension, "beating the competitor to the ball" to improve quickness, or attempting to "knock down a wall" with a powerful medicine ball toss (70,71) (*Figure 11*). Non-contact ACL injuries may happen from the athlete's failure to maintain sufficient neuromuscular knee control as they attend to external focus stimuli such as a moving ball or competitor, with highly complex dynamic visual input, and movement planning on different playing surfaces with different footwear, and rapid, unanticipated decision making (72). Consciously focusing on an individual component such as bending the knees more when jumping

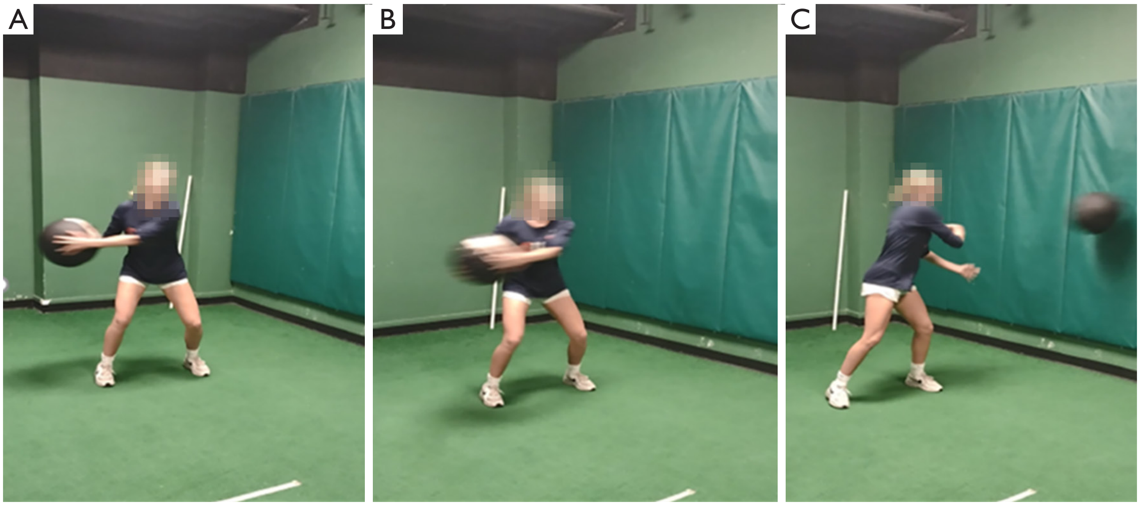

Figure 11 Long-axis rotational medicine ball toss with an external cue to "knock down the wall". (A) Cocking; (B) acceleration; and (C) explosion. A whole-body long axis rotational movement using plyometric principles to improve upper extremity-trunk-lower extremity coordination while maintaining approximately 20°–30° knee flexion. These images are published with the participant's consent.

(internal focus of attention) rather than on the aggregate functional movement effect, such as "exploding up from, and off the ground" disrupts the natural automatic motor control regulatory process (70,71). In contrast, by directing the focus of attention more externally to holistic movement outcomes, the motor control system makes actions quicker, more automatic, and more reflexive (73-75). Decreased corticomotor excitability under the same task demands shifts control to lower-level subcortical motor regions increasing automaticity with less need for higher level cognitive engagement (76,77). Neuroplasticity occurs as greater movement skill develops during tasks as diverse as leg pressing, single leg jump landings, and postural stabilization tasks. Long-term training-induced neuroplastic changes with diminished neuromuscular excitability indicates improved motor plan efficiency, automaticity, and coordination, and perhaps greater central and peripheral fatigue resistance (78).

During sport movements, the athlete's neurocognitive system interacts with environmental stimuli (37). To develop an effective movement strategy, they must evaluate constantly changing, highly complex unpredictable situations (e.g., movement of a teammate, an opponent, or a ball), efficiently processing situation-specific visual-spatial cues. These movement strategies can be differentiated into space, time and form dimensions (79-83). Qualitative and quantitative appraisals of athletic movement performance should consider each of these dimensions. Failure to appreciate, search, process, accurately interpret, and appropriately act upon environmental information may result in performance deficits and/or knee re-injury.

Instructional cues that induce an external focus of attention during single leg jumps increases knee and ankle flexion (84), reduces peak ground reaction forces (85), and enhances performance (86) more than internal focus of attention cues. To better map the sensations associated with motor actions, higher cognitive level integrative processes are foundational to early adaptive and anticipatory postural control dynamics (71). Greater use of external focus of attention cues during neuromuscular control training can improve task performance, generating more automatic responses, with improved lower extremity landing biomechanics, enhancing knee injury prevention (87). By better controlling net tibiofemoral shear forces through quadriceps and hamstring muscle coactivation, external focus of attention cues can be particularly helpful during single leg jumping or directional change movement tasks that possess higher ACL injury risk (88). With appropriate external focus of attention cue use, task automaticity increases, jump landing technique improves, jump height increases, and ACL injury risk decreases (87,89). After a 9-week training program, Makaruk *et al.* (89) reported that healthy subjects who only received external focus of attention cues had greater standing long jump distance, with increased peak knee flexion, and increased contact time compared to subjects who only received internal focus of attention cues.

Figure 12 Single leg lateral step-overs. While holding a soccer or volleyball overhead, the athlete steps diagonally over caution tape placed either on the floor or 2–12 inches (5–30 cm) off the floor over a 15-m distance. Going barefoot, more slowly, and eyes closed increases the movement challenge. This image is published with the participant's consent.

Within any environment, ecological dynamics and social cognition factors integrate ideas from psychology and dynamic systems theory to improve adaptive learning and behaviors (90-92). The ecological dynamics and social cognition approach to perception, knowledge, action, and skill acquisition initially breaks down or destabilizes existing behavior or coordination capabilities. Then, through guided practice, the athlete re-organizes their behavior or coordination capabilities to increase affordance boundaries better overcoming movement dilemmas, becoming more comfortable exploring new environments, and better processing action strategy and tactic development (90-93). Strategy is the plan that an athlete uses to achieve their objective. Tactics are the actions that athletes use to achieve the selected strategy. Understanding how well these important factors synchronously link, given an athletes' interests and expectations, experience, skill level, personality, conditioning, and injury recovery status, are important (4). Within this context, constraints are temporary boundaries that can shape the emergence of an athlete's developing cognitions, actions, and decision-making. Constraints represent multi-factorial considerations that may include factors such as the athlete's cognitive appraisal of their injury, skill and technical abilities, conditioning level, injury history, capacity to tolerate pain or fear, motivations, expectations, and perceptions. Given time and a reason to reflect about and adapt to changing conditions the athlete can develop a better understanding of their own inherent constraints (90-95).

Agility, metabolic energy system, and fatigue resistance training

Depending upon the specific sport, position played within that sport, and style of play, foundational metabolic energy system function should be restored as the athlete transitions from progressive baseline, longer duration, unidirectional, slow speed distance walking-jogging-running to multi-directional, high speed, shorter duration, higher intensity or frequency (total volume) sprinting and jumping tasks. The most decisive efforts that dictate sports movement successes or failures are often highly anaerobic involving sudden directional change movements. As such, restoring explosive lower extremity movement acceleration, deceleration, and directional change capabilities is essential to return to sports participation. Depending upon task duration, explosive movements challenge the adenosine triphosphate (ATP), creatine phosphate (CP) (≤10 sec), and glycolytic anerobic energy systems (up to 120 sec). After successful completion of slow speed tasks (*Figure 12*), examples of agility tasks designed to task the CP-ATP and glycolytic anerobic energy systems depending upon intensity levels and duration include the circuit cutting drill (*Figure 13A*), the mirror reaction drill (*Figure 13B*), a 5–15 m shuttle run (*Figure 13C*), and short-ball-tall (*Figure 13D*). Different sports movement tasks and work: rest cycle requirements generate different metabolic energy system demands which can be addressed by manipulating movement intensity, duration, rest periods, and total volume. By mid-to-late rehabilitation, a minimum baseline aerobic and anerobic energy system recovery level should be re-established based on individual athlete performance needs.

In addition to metabolic energy system deficiencies, acute peripheral or central nervous system fatigue can alter lower extremity neuromuscular function and biomechanics (96-101). Altered sports movement quality in the presence of fatigue may increase proximal tibial anterior shear, decrease hip and knee flexion, and increase knee valgus and internal rotation (1). Lower extremity neuromuscular control system impairment/fatigue in the presence of lower extremity strength or biomechanical alignment impairments during unanticipated movements typical to sports participation further increases the risk of ACL injury (99,100). Therefore, it is important to

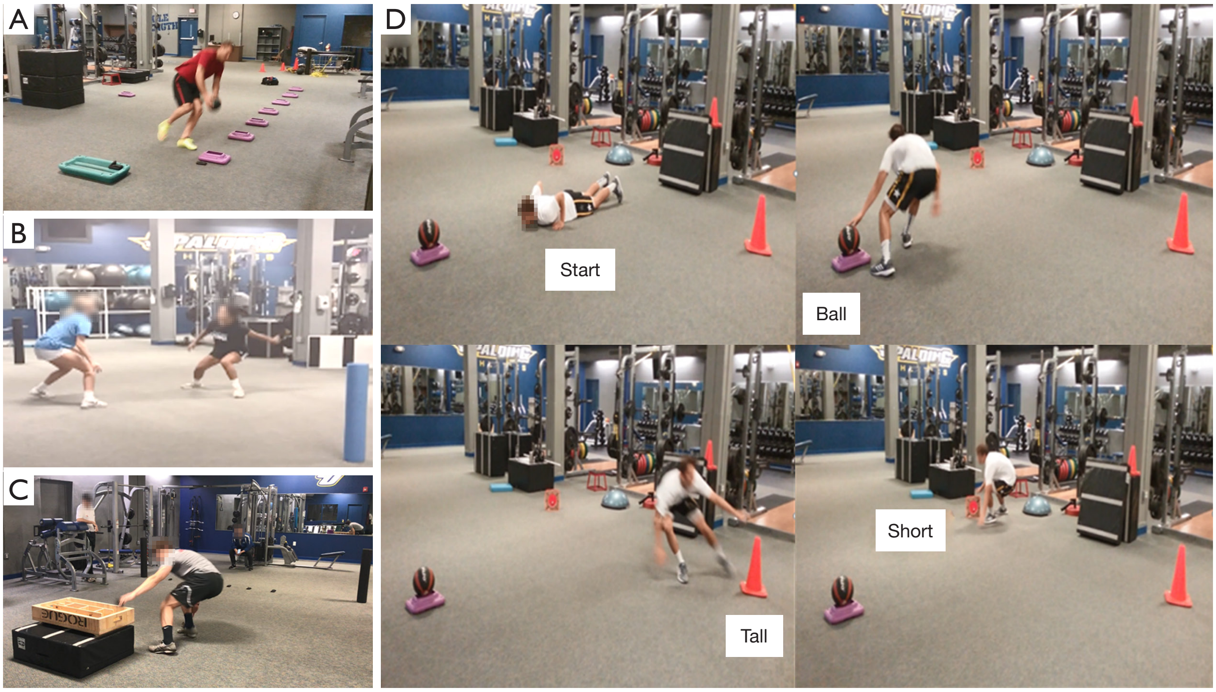

Figure 13 Agility movements. (A) Circuit. As the athlete moves from the center toward the periphery, they place a 6 lb (2.7 kg) medicine ball in each "socket" before grabbing a 1 lb (0.45 kg) weight and moving it to the opposite side bin. This explosive movement challenges repetitive dynamic knee stability during running directional change cuts in a manner that highly tasks anerobic energy system function; (B) Mirror reaction drill. Athletes take turns being on offense or defense. As the offensive player moves forward toward the defensive player, the defensive player prepares for their sudden 90° directional change and tries to beat them to the pylon; (C) 5–15 m Shuttle Run ("Blackjack"). The athlete attempts to sequentially move 7, 1 lb (0.45 kg) pellets to a bin in ≤21 sec (for 5 m). A challenging test of explosive quickness and anerobic energy system function; (D) Short-Ball-Tall. Beginning in the center of a triangle formed by short and tall cones, and a ball, and alternating between prone and supine starting positions, the athlete responds to a series of 3 word cues (e.g., SHORT-BALL-TALL; BALL-TALL-SHORT, etc. repeats) to touch the requested object in sequence without turning their back to the timer. This movement assesses agility, anerobic energy system function, and helps determine the athlete's resilience for getting up and off the ground when fatigued. A series of 3–5, 30 sec bouts is performed. These images are published with the participants' consent.

confirm that the athlete possesses acceptable unplanned as well as planned movement performance quality under peripheral or central neural system fatigue conditions (1). Accumulated mechanical tissue fatigue over the course of repetitive training sessions or competitions may also elevate ACL injury risk (1,100,101). Managing training loads and minimizing exposure to prolonged training load elevations is important to both primary ACL injury prevention and re-injury prevention (1). Athletes who are stronger and more physically and mentally fit better tolerate elevated acute: chronic workload ratios and avoid re-injury (102), emphasizing the importance of developing their overall physicality, fatigue resistance, and resilience. At 6 months post-ACL reconstruction, soccer players who successfully completed standard rehabilitation still had impaired aerobic fitness (VO_2 max) (103). Therefore, exposing athletes to peripheral or central neural system fatigue conditions during rehabilitation may better prepare them to withstand the excessive training loads and fatigue-related strength loss that they may encounter upon returning to sports. In addition to using progressive training overload concepts to improve metabolic energy system function, it is vital that the recovering athlete understand and obtain proper nutrition including protein, complex carbohydrate, dietary fat, vitamin and mineral intake levels (104).

Isolated and integrated neuromuscular responsiveness

Although moderate-load resistance training (8–12 repetitions

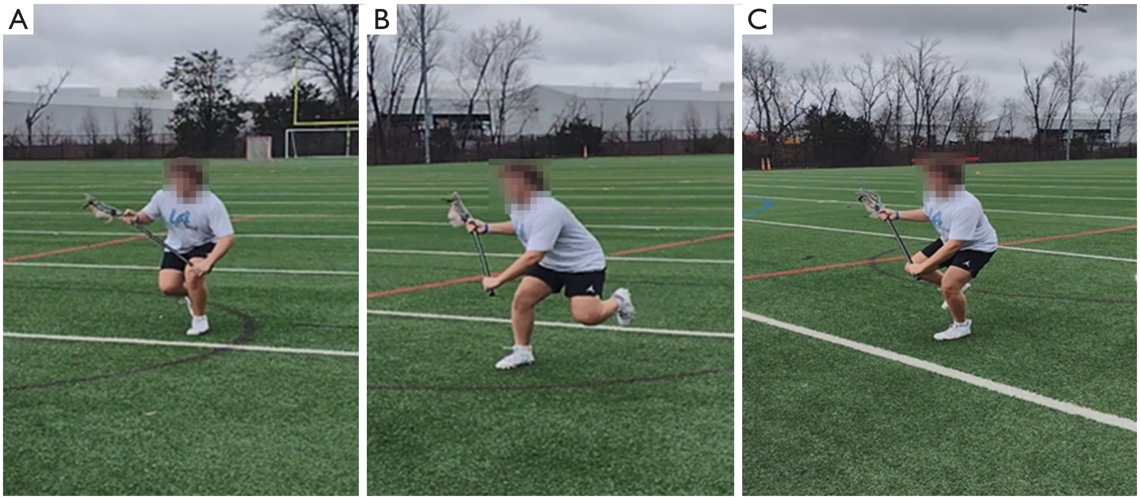

Figure 14 Speed skaters. A single leg hop triplet of LEFT-RIGHT-LEFT (or RIGHT-LEFT-RIGHT), hopping quickly and wide to the left (A), then quickly and wide to the right (B) before hopping to the left again and stabilizing on left leg with a flexed knee for 2–3 seconds (C). Repeat this triplet or alternate with right-left-right for 20 m. With lacrosse stick in hand or a soccer ball held overhead, this movement provides a useful method to evaluate dynamic knee stability during repetitive single leg loading. These images are published with the participant's consent.

with 70% of an athlete's maximal load) can increase muscle size and strength, it does not provide sufficient stimulus to improve maximal peak force or torque rates (105-108). The athlete's ability to rapidly produce lower extremity neuromuscular forces when sprinting or jumping from a baseline of relatively low neuromuscular pre-activation is more important than how much peak strength or torque they can produce starting from total relaxation (1). To optimize performance (109-110) and prevent injury (111), the athlete must be able to quickly generate high forces (111-113). To better restore and measure lower extremity neuromuscular force or torque development rates, mid-to-late-stage rehabilitation and bridge programs should incorporate mixed isolated and integrated lower extremity muscle group explosive movements (114) (*Figures 14,15*). Knee extensor force development rates are impaired after ACL injury and reconstruction (113) contributing to decreased self-reported knee function (111,115,116). Restoring pre-morbid knee extensor force or torque development rates is vital to recovery (1). To better delineate true residual impairment levels, recovering athletes should compare favorably to either their own pre-morbid condition, or to matched healthy athletes. The ability to rapidly re-stabilize the knee in <50 ms following mechanical perturbation can assist with knee re-injury prevention (117) or improved explosive volitional task performance such as sprinting or jumping (100–120 ms) (118). After 4–8 weeks of specialized training, the force development rates of healthy athletes can improve by 50–80% (108). Angelozzi *et al.* (111) identified 30% concentric knee extensor force rate development deficits 6 months post-ACL reconstruction despite fully restored maximal concentric knee extensor strength. Through a lower extremity neuromuscular power development program, normalcy was achieved by 12 months post-surgery. Although peak neuromuscular force or torque capability occurs ≥150 ms after initial activation, knee extensor force or torque development rates 0–50 ms (early) or 0–100 ms (mid-phase) are more closely linked with baseline neuromuscular pre-activation levels, muscle contractile properties, fast twitch muscle fiber health, and improved architectural muscle characteristics (112,119). Decreasing lower extremity neuromuscular activation reaction time reduces the likelihood of knee joint re-injury. To confirm knee extensor and flexor muscle group rate of force or torque development, both open (isolated muscle group) and closed (integrated muscle groups) evaluations should be performed (114).

Neuromuscular control and dynamic knee stability

Neuromuscular stiffness dynamics are determined by: (I) intrinsic muscle properties (non-reflex stiffness); (II) force feedback from ensemble or "collaborative group" information such as from Golgi tendon organs; and

Figure 15 Plyometric movements. (A) Bounding. This task attempts to maximize vertical elevation with forward momentum through explosive, alternating lower extremity neuromuscular activation. The goal is to achieve similar bilateral single leg jumping height and a controlled, symmetrical landing style; (B) two-legged Kangaroo Hops. A series of explosive continuous hops intended to achieve maximum vertical height and smooth symmetrical landings over 20 m. This progresses to one-leg kangaroo hops; (C) double to single leg lateral hops. The same as single leg lateral step-overs, replacing the non-impact step with explosive double or single leg diagonal hops over caution tape for a 15 m distance while holding a ball overhead; (D) frog hops. A series of explosive hops to achieve maximum horizontal distance and smooth symmetrical landings over 20 m. The athlete can rest momentarily between hops. These images are published with the participants' consent.

(III) length feedback provided by ensemble information from muscle spindles (120,121). Musculotendinous, capsuloligamentous, and cutaneous receptors each contribute sensory information to the neuromuscular control system. Dynamic knee joint stability challenges such as side-step cutting alter lower extremity muscle force and length feedback. As the athlete grips, contacts, or carries an object like a ball, stick or bat, knee joint loading force magnitude and location changes, especially when the object is manipulated farther away from the rest of the body (122). Therefore, holding an object like a stick, bat, racquet, or ball during movement education activities/tasks can change dynamic knee joint stability challenges.

Dynamic stability is resistance to postural displacement and the ability to maintain equilibrium or resume an original posture after a sudden perturbation (57,123). Dynamic knee joint stability represents the ability to overcome sudden shifting, buckling, or giving way sensations (124) or the ability to remain stable when joint loads rapidly change during activity (121). Composite dynamic knee stability is dependent not only on the primary knee joint muscles (quadriceps femoris and hamstrings), but also on trunk, lumbopelvic, hip, and ankle muscle function. Dynamic stability through the ankle and subtalar joints, and the foot is provided by both intrinsic or "core" foot muscles and extrinsic leg muscles with contributions from more proximal muscles acting primarily through the hip and knee joints (1,59,123,125,126). Dynamic joint stability provided through local (knee), regional (lower extremity), and global (whole body) neuromuscular activation is of high importance to rehabilitation clinicians because it may be the only dynamic joint stability component that can be directly improved through well-designed therapeutic exercise program application.

Neuromuscular control is the ability to produce coordinated movements through properly modulated neuromuscular activation during which feedback and feedforward systems work together through ensemble averaging of input from multiple receptors (120,121). Postural control represents the ability to control the body's center of mass with proper orientation within its stability limits. To maintain balance and postural control the neuromotor system uses sensory information from three sources: (I) somatosensory feedback from peripheral receptors; (II) vision; and (III) the vestibular system (121). Visual input provides the athlete with posture and movement verticality references in relation to other objects. Vestibular input provides information about head position and movements in relation to gravity and internal forces. Postural support base perturbations are a useful method for clinically examining neuromuscular recruitment patterns and postural control synergies (55,121,126-128). When a forward-directed sway is induced from a posterior horizontal perturbation, posterior muscles such as the gastrocnemius, hamstrings, gluteus maximus, and erector spinae are recruited. In contrast, anterior muscles such as the tibialis anterior, quadriceps femoris, hip flexors, and rectus abdominis are recruited when a backward-directed sway is induced from an anterior horizontal perturbation. When postural equilibrium perturbation is small and the support surface is firm, an "ankle strategy" may be sufficient to return the body's center of mass back to postural stability. However, when larger perturbations to stance are experienced, when the surface is unstable, or if the athlete is unable to generate sufficient force using an ankle strategy alone, a "hip strategy" may be needed. When the perturbation is so strong that it displaces the athlete's center of mass outside their support base, a "stepping strategy" may be needed where they must take a step or a hop to restore postural stability (121). Perturbations that create diagonal stepping patterns require greater and more varied multiplanar movement responses (5,121).

For the athlete preparing to return to sports after ACL injury, surgery, and rehabilitation, the end goal should focus on developing their capacity to self-organize optimal dynamic neuromuscular control and dynamic joint stability during new, challenging movement experiences. They need to understand the important risk-benefit balance between exploiting new motor learning experiences and the limits of safe exploration. Increasing the recovering athlete's adaptability in terms of motor plan development, storage, and information processing efficiency is important. As the athlete performs a mix of routine and more novel, sometime chaotic movements, they improve neuromuscular control and coordination near their instability boundaries, learning about what is their individual optimal blend of safe movement variability in the presence of sufficient dynamic knee joint stability (66,129). For this reason, neuromuscular control training should be exploratory, characterized by persistent perception-action system excitation during novel performatory movements that involves the purposeful application of previous exploratory movement experiences. Manipulating the therapeutic movement-based exercise environment is essential to help them develop the neuromuscular control and dynamic lower extremity stability needed to decrease knee injury or re-injury risk.

Strengths and limitations

An important limitation was that program participants primarily consisted of non-elite athletes (2). Therefore, we do not know how effective the program would be with elite level athletes. A study strength was the diversity of sports that adolescent and youth athletes participated in, which included soccer, basketball, softball, football, baseball, tennis, volleyball, field hockey, lacrosse, ballet, gymnastics, cheerleading, wrestling, downhill skiing, badminton, track and field, motocross, and taekwondo.

Conclusions

Use of this program prior to release back to unrestricted sports decreased ipsilateral knee re-injury and contralateral knee injury rates compared to previous reports (2,31-33). This program also provided athletes with a greater opportunity to reflect about their true sports readiness prior to being released back to unrestricted sports participation. A combination of limited recent sport task experiences, high athletic self-identity, and obsessive sport passion may lead many youth and adolescent athletes to be released back to unrestricted participation too soon. Well-designed return to sport bridge programs can effectively transition the athlete from early dependence on higher executive level cognitive brain function to lower level, more automatic responses when confronted with the random perturbations or unexpected chaos common to many sports. Athlete reported function assessments should be combined with evidence-based objective clinical and field testing information. Determining the best blend and timing of evidence-based criterion-based assessments is greatly needed. Following program completion, all athletes are instructed in the need for continued neuromuscular control training to maintain sports participation readiness (2,21).

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Footnote

Peer Review File: Available at https://aoj.amegroups.org/article/view/10.21037/aoj-23-3/prf

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Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All images included in this review are published with the participants' consent.

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