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Functional Training for the Restoration of Dynamic Stability in the PCL-Injured Knee

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Functional training for the purpose of restoring dynamic joint stability has received considerable interest in recent years. Contemporary functional training programs are being designed to complement, rather than replace, traditional rehabilitation protocols. The purpose of this clinical commentary is to present a management strategy for restoring dynamic stability in the posterior cruciate ligament (PCL)–injured knee. The strategy presented integrates five key concepts: (a) planned variation of exercise, (b) outcomes-based assessment, (c) kinetic chain exercise, (d) proprioception and neuromuscular control, and (e) specificity of activity. Pertinent research findings and a clinical rationale are provided for using functional training in the restoration of dynamic stability in the PCL-injured knee.

Key Words: planned variation, kinetic chain exercise, proprioception, specificity

Functional training for the purpose of restoring dynamic joint stability has received considerable interest in recent years. Functional training evolved from the perception that traditional rehabilitation programs were not adequately returning athletes to their desired preinjury performance levels (18). As a result, contemporary functional training programs are being designed to complement, rather than replace, traditional rehabilitation protocols (36). Emphasis is placed on matching the neuromuscular and physiologic demands of the exercise with the demands of the athlete's sport (18, 36).

Many functional training programs promote proprioception and neuromuscular control training as an integral subcomponent to the overall program (6, 16, 18, 20, 21, 25, 30, 36, 38). The role of proprioception and neuromuscular control

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in functional training is well established (6, 20, 21, 25). Research by Lephart and coworkers at the University of Pittsburgh identified proprioceptive deficits in anterior cruciate ligament (ACL)– and posterior cruciate ligament (PCL)–deficient and –reconstructed knees (5, 14, 22, 33) and clinically unstable glenohumeral joints (26). Similar research revealed a strong relationship between proprioceptive acuity and functional performance in healthy (19), ACL-deficient (4), and postsurgical knees (1). Athletes displaying greater proprioceptive acuity demonstrated greater knee function. We postulate that the same is true for the PCL-injured athlete. Lephart et al. concluded that proprioception was a clinically relevant physiologic variable that needed to be addressed in order to sufficiently restore dynamic joint stability (5, 6, 20, 21, 25).

Posterior cruciate ligament injuries have received increased attention during the last decade, but the body of knowledge concerning the prevention, recognition, and treatment of PCL injuries lags far behind that of ACL injuries. To date, no study has presented a management strategy for restoring dynamic stability in the PCL-injured knee. The purpose of this clinical commentary, therefore, is to present a management strategy for restoring dynamic stability in the PCL-injured knee. Pertinent research findings and a clinical rationale are provided for using functional training in restoring dynamic stability.

Mechanical and Sensory Role of the Posterior Cruciate Ligament

Similar to the ACL, the PCL has a dual role in knee-joint stability. Mechanically, the primary role of the PCL is to limit posterior displacement of the tibia from the femur (11, 13, 15, 32), and the neurologic role of the PCL is to relay afferent information to the central nervous system (CNS) concerning joint position and motion (14, 31, 33). Together, both roles function in controlling normal knee arthrokinematics.

The effect of ligamentous injury resulting in mechanical instability and proprioception deficits contributes to altered arthrokinematics, which can eventually develop into a functionally unstable or disabled joint (Figure 1) (20, 25). Increased episodes of functional instability and disability can lead to a vicious cycle of repetitive microinjury to the joint (20, 25).

Eakin and Cannon (11) were able to reveal increased posterior tibial translation compared with healthy knees, supporting the postulate of mechanical instability. The sensory role of the PCL has only recently been investigated. Raunest et al. (31), using an animal model, were able to demonstrate the existence of a proprioception mechanism between the PCL and the quadriceps and hamstring muscle groups. They found that when the PCL was loaded, the quadriceps was activated and the hamstrings were simultaneously suppressed. They concluded that there is a proprioceptive mechanism arising from PCL loading, and the magnitude of the load subsequently regulates knee-joint stiffness. Similar research revealed proprioception deficits in

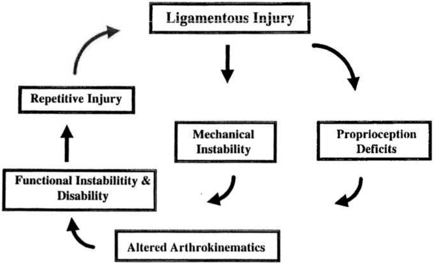

Figure 1 — Clinical paradigm depicting the coupled effect of mechanical instability and proprioception deficits leading to functional instability and disability. Adapted with permission of Human Kinetics from Lephart and Henry (20).

PCL-injured knees. Clark et al. (8) and Safran et al. (33) found that the knees of patients with PCL deficiency displayed significant kinesthetic deficits when compared with healthy knees. Conversely, Giraldo et al. (14) demonstrated no significant deficit in PCL-reconstructed knees when compared with healthy knees. These findings support the postulate that a proprioceptive mechanism exists between the PCL and the CNS at the spinal and supraspinal levels. They also suggest that there are proprioceptive deficits after PCL injury, and subsequent surgical reconstruction might play a significant role in restoring knee proprioception to near-normal levels.

Researchers investigating muscle function in PCL-deficient knees have identified the existence of compensatory muscle activity (7, 17, 37). They have suggested that the aberrant muscle-firing patterns occur as a means to compensate for altered knee arthrokinematics resulting from mechanical and proprioceptive deficits. Cain and Schwab (7) described an insufficient quadriceps mechanism as a result of PCL injury (Figure 2). In this pathomechanism the tibia subluxes posteriorly from the femur, creating a reduced mechanical advantage as a result of the posterior tibial displacement (7). If this pathomechanism is allowed to persist, increased pathologic wearing of the tibiofemoral joint, especially the medial aspect, as well as patellofemoral dysfunction, has been suggested to result (7, 39). Several studies using EMG analysis were able to show compensatory quadriceps (7) and gastrocnemius (17, 37) preactivation in PCL-deficient knees during gait and open kinetic chain knee extension. Cain and Schwab (7) found that the quadriceps muscle

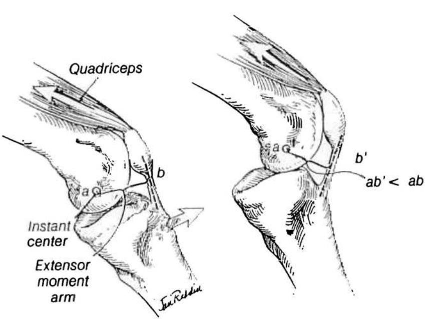

Figure 2 — Pathomechanism depicting altered knee kinematics due to posterior subluxation of the tibia on the femur. Reprinted with permission of the *American Journal of Sports Medicine* from Cain and Schwab (7).

group of the PCL-deficient knee preactivated prior to foot strike. Tibone et al. (37) and Inoue et al. (17) both demonstrated early and prolonged gastrocnemius activation. This pattern of muscle preactivation is reported to limit posterior tibial displacement during gait.

Limiting posterior tibial displacement in PCL-injured knees is particularly important during early rehabilitation. Ohkoshi et al. (27) and Wilk (39) revealed excessive posterior tibial shear when the trunk was forward-flexed during a squat exercise. Therefore, special care should be taken to prevent posterior tibiofemoral shear and maintain adequate patellofemoral function during early-, intermediate-, and late-stage rehabilitation.

Restoring Dynamic Stability

Posterior cruciate ligament injuries are categorized according to time (acute or chronic) and severity (isolated or combined) (15, 32). Research suggests that isolated PCL injuries most commonly occur as a result of sport participation (15). Most isolated PCL injuries are treated conservatively and have an excellent prognosis (15, 29, 32, 34). Conversely, combined ligament injuries often result in surgical repair and have a less favorable prognosis (15, 29, 32, 34). Isolated PCL injuries are classified as partial (Grade I or II) or complete (Grade III) tears. Researchers report a higher incidence of partial (Grade I or II) tears in athletes (15) than Grade III tears. This underscores the importance of a thorough clinical evaluation prior to developing a comprehensive management strategy (32, 34).

The clinical outcome of PCL injury is suggested to largely depend on dynamic quadriceps function (39). Limiting excessive posterior tibiofemoral shear stress and restoring proprioception and neuromuscular control have been implicated as major factors in restoring dynamic stability in the PCL-deficient knee (39). The management strategy for restoring that stability should follow existing strategies prescribed for knee ligamentous injuries. The emerging functional training strategies should be used to complement, rather than replace, traditional protocols that focus on controlling pain and inflammation, while restoring full pain-free range of motion, muscular strength, power, and endurance (36). The sports medicine practitioner must design a comprehensive management strategy that addresses the deficiencies detected on physical examination that affect dynamic stability and, ultimately, functional performance. Accelerated rehabilitation protocols for the ACL have increased in popularity over the past decade, and similar strategies might be implicated for PCL injuries (2, 9, 35). The strategy we present integrates the following key concepts: planned variation of exercise, outcomes-based assessment, kinetic chain exercise, proprioception and neuromuscular control, and specificity of activity.

Key Concepts for Functional Training

Planned Variation of Exercise (Periodization). The theory behind using a planned-variation, or periodization, model involves a proactive manipulation of exercise variables in order to optimize adaptations. The planned variation provides a consistent positive stimulus that results in desired physiologic adaptations, leading to a successful functional outcome. The variables of importance include overload (intensity), volume (sets, repetitions, and rest), frequency, recovery, and mode. By careful manipulation of these variables an athlete is afforded adequate stimuli that safely challenge the injured limb. Periodization models have been used extensively by strength and conditioning specialists, with documented success (12). We feel that the same rationale should be applied to rehabilitation and functional training strategies.

Outcomes-Based Assessment and Reassessment. Clinical outcomes determine the success or failure of a rehabilitation program from both the clinician's and the patient's perspectives. Assessment of outcome must be performed repeatedly at specific intervals during the course of the rehabilitation program and should include both subjective and objective data. Patient-report (3, 4, 23) and performance-based (4, 23, 24) measures of function have been used extensively to provide accurate feedback on patients' functional progression.

Kinetic Chain Exercise. Much literature has been devoted to explaining the advantages of open and closed kinetic chain (CKC) exercise in the rehabilitation

program. Open kinetic chain (OKC) exercise has been described as an "isolationist" form of exercise in that singular muscle groups are trained (28). CKC exercise has been described as synergistic, in that multiple muscle groups act to provide stability and mobility for an entire kinetic chain (i.e., a lower extremity) (10, 20, 28). Closed kinetic chain exercise has also been suggested to be a safer form of exercise in which external and internal forces are dispersed over a broader range of skeletal and soft-tissue structures (10, 28).

Proprioception and Neuromuscular Control. Proprioception encompasses the conscious and unconscious sensations of joint position and motion and is mediated by afferent input from central and peripheral mechanoreceptors (25, 36). Developing a functional training program that incorporates proprioceptively mediated exercise necessitates an appreciation of the CNS's influence on neuromuscular control. This afferent feedback is appreciated by the CNS and is used to modulate efferent responses at the spinal and supraspinal levels. These efferent responses are termed neuromuscular control and involve the transformation of neural information into physical energy (20, 25, 36). The approach to restoring dynamic stability should encompass the neurosensory subsystems (somatosensory, visual, and vestibular) and the levels of neuromuscular control (spinal reflexes, cognitive programming, and brain stem activity), as proposed by Lephart and Henry (20) (Figure 3). The objectives of proprioception and neuromuscular control training are to enhance sensation of the injured joint by retraining altered afferent pathways and to recruit secondary somatosensory and visuovestibular pathways (20, 25). For an in-depth review of proprioception and neuromuscular control, see Lephart et al. (20, 25) and Swanik et al. (36).

Specificity of Activity. The next functional training objective is to develop and/or restore functional and sport-specific motor patterns. Through repetition of desired activities, the sensorimotor cortex stores these motor patterns as central commands. During functional performance the motor patterns are activated and

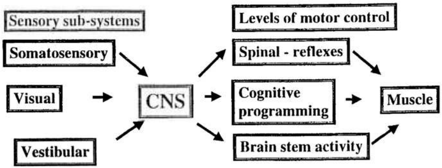

Figure 3 — Clinical paradigm depicting the sensory subsystems and neuromuscular control pathways. Adapted with permission of Human Kinetics from Lephart and Henry (20).

work synergistically with subcortical regulators to provide dynamic joint stability during controlled movement (25). Early implementation of sport- and activity-specific training that addresses altered proprioceptive and neuromuscular control pathways provides the stimulus for cognitive motor programming and reflex muscular stabilization. Over time, these motor programs function at the subconscious level without continuous reference to consciousness (20, 25, 36).

Clinical Applications

Although early-stage implementation and progression of a functional training program will vary between operatively and nonoperatively managed cases, the proposed program is not determined by management selection. Rather, the implementation and progression depend on clinician experience and preference, as well as the condition of the athlete and his or her comfort level and responsiveness to the exercise. Among contemporary orthopedic surgeons, considerable controversy exists over the appropriate time after surgery at which functional stresses should be initiated, particularly following ACL reconstruction (2, 9, 35). Therefore, we do not offer a time continuum relative to implementation and progression; rather, we advocate a progression based on outcomes assessment.

Once the patient has significant resolution of pain and swelling, progressive resistance exercise should be incorporated into the rehabilitation program. Aggressive OKC quadriceps exercise is indicated to restore dynamic quadriceps function in the early stages, whereas resisted knee-flexion exercise in the open kinetic chain is contraindicated, in order to prevent posterior shear forces on the joint (39). Once dynamic quadriceps function has been established, the clinician should direct his or her focus to reestablishing proprioception and neuromuscular control. The training should be progressive in nature and should address all sensory subsystems and levels of sensorimotor control (Figure 3). The long-term goal of functional training is a safe return to full function with minimal risk of reinjury. Transitional exercise should be integrated into the progression plan to provide a safe and gradual adjustment to the newly imposed demands. Progression criteria in the form of qualitative and quantitative data are recommended to ensure that treatment goals are being met (18, 30, 38). The exercise should be energy system–specific, thereby ensuring that the metabolic demands of the activity are being met. Additionally, the exercise should address the neuromuscular demands of the athlete. Using the paradigm proposed by Lephart et al. (20, 25), a functional training program can be designed by carefully manipulating the neurosensory feedback pathways for the purpose of inducing specific neuromuscular control patterns that aid in dynamic stability of the PCL-injured limb. Additionally, each stage of the functional training program should address the four elements necessary for restoring neuromuscular control: kinesthetic awareness, dynamic stabilization, reactive neuromuscular control, and functional motor patterns (20, 25, 36).

Early Stage

In the early stages of functional training, minimal impact is recommended to prevent unwanted stress to the joint. Additionally, core stability is desired in order to achieve a stable pelvic base. A stable pelvis enables the biarticular muscles of the hip and knee to function efficiently by maintaining an adequate length–tension relationship throughout a desired range of motion (28). The early stage should focus on enhancing kinesthetic awareness and muscular endurance of the involved limb.

For the PCL-injured athlete, a simple wall-sit and/or -slide model can be used to effectively train the neuromuscular system to consciously recognize joint position and motion. The recumbent position of the wall sit eliminates excessive forward trunk flexion, thus preventing any unwanted posterior tibial translation (27, 28, 39). The static wall-sit maneuver can begin in a neutral position of knee flexion (90°) and eventually progress to multiple angles of flexion and extension. The static positions can be held for variable periods of time, using multiple repetitions followed by short recovery periods. This static CKC exercise enhances kinesthetic awareness, as well as quadriceps strength and endurance. The exercise uses fixed, stable proximal (wall) and distal (floor) boundaries, with minimal load on the involved joint. Resistance is applied in an axial fashion, using body weight and gravity dependence.

The planned progression scheme can involve any of the following proposed combinations in any sequence. The objective is to progressively increase the difficulty and complexity of the task in a systematic fashion. The early-stage functional progression scheme might involve the following:

- Progressing from fixed, stable proximal and distal boundaries to fixed, unstable proximal and distal boundaries. An unstable boundary can be achieved proximally with a Swiss ball between the back and wall and distally by standing on foam rolls or a minitramp (Figure 4a).
- Progressing from a static to a dynamic movement pattern using controlled concentric and eccentric activity in a designated arc of motion (30–120° flexion).
- Progressing from eyes open to eyes closed.
- Progressing from body-weight resistance to increased axial loading using a weight vest.
- Applying an external perturbation force using a sport cord or rubber tubing (Figure 4b).
- Progressing from a double- to a single-limb stance.
- Incorporating distracting stimuli such as a ball toss or other sport-specific activity.

Next, the athlete can progress from a wall-sit maneuver to a more upright stance to further increase the functional challenge. This position simulates the squat maneuver. Again, the athlete can follow a similar progression scheme:

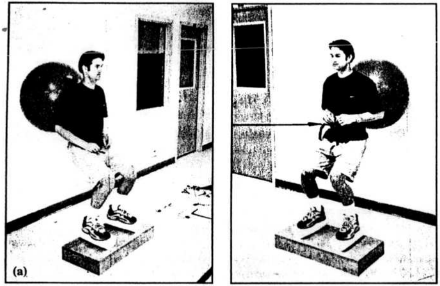

Figure 4 — Wall sit or slide. (a) Alteration of the proximal and distal boundary conditions. (b) Inclusion of external resistance with eyes closed increases the difficulty of the task.

- Fixed, stable distal boundary to a fixed, unstable distal boundary
- Double- to single-limb stance (Figure 5a)
- Eyes open to eyes closed
- External perturbation and resistance (e.g., weight vest)
- Distracting stimuli (e.g., ball toss; Figure 5b)

The desired neuromuscular adaptations include enhancing kinesthesia and dynamic control of the quadriceps. By moving to the upright posture the athlete will begin to use quadriceps, hamstring, and gastrocnemius coactivation to help dynamically stabilize the joint. External perturbations increase reactive and preparatory activity, thereby stimulating the reflex pathways necessary to increase muscle stiffness (36). Similarly, by increasing the complexity of the task, the athlete is forced to concentrate on other stimuli, thereby performing the exercise without continual reference to consciousness. The importance of reactive training was demonstrated over a decade ago (16).

Transition exercises are incorporated once progression criteria have been met or exceeded. Performance-based measures include balance and postural tests and/or force-production tests using an isokinetic dynamometer. Patient-report measures include knee rating and analog scales. If bilateral deficits exceed 30%, progression is contraindicated until such time as adequate improvement is demonstrated (38, 39).

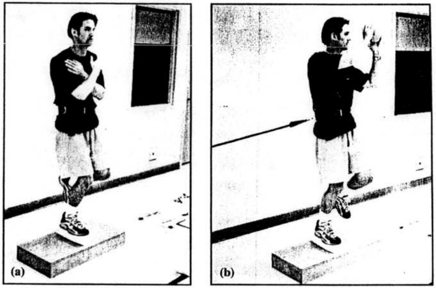

Figure 5 — Single-limb stance. (a) Unstable distal boundary. (b) External perturbation with distracting stimuli.

Intermediate Stage

Transition to the intermediate stage requires that the athlete perform exercises of low to moderate impact and resistance, longer durations, and greater complexity. The Pro Fitter, or slide-board device, is an excellent mode of training in the intermediate stage (Figure 6a). The athlete can begin with low resistance and high repetitions in order to become familiar with the task and develop basic motor programs. This mode of exercise requires the synergistic use of reactive, preparatory, and conscious muscle activity to propel the body laterally while dynamically stabilizing the PCL-injured knee.

Once accustomed to the activity, the athlete can progress to using added internal (weight vest) and/or external (sport cord) resistance (Figure 6b). Multidirectional perturbations using sport cord tubing or a medicine ball increase the complexity of the task and ultimately enhance neuromuscular control. The athlete can progress from eyes open to eyes closed. This should only be done if the athlete perceives the environment as being safe. The use of random external perturbations is effective in challenging the athlete to use reactive and preparatory mechanisms to stabilize the joint. These mechanisms are used to facilitate the development of preprogrammed muscle stiffness (36). These moderately complex tasks incorporate synergistic coactivation of the quadriceps, hamstring, and gastrocnemius muscle groups. Additionally, the activity requires the muscles to act concentrically, eccentrically, and isometrically.

A good transitional exercise is the lunge, which requires low to moderate impact and prepares the athlete for moderate- to high-impact exercise in the late stage.

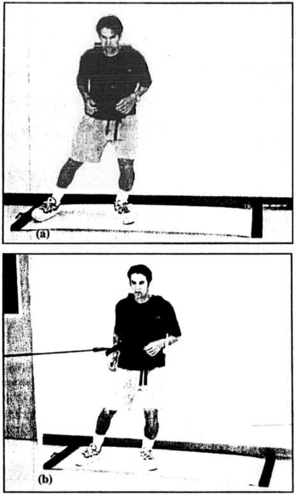

Figure 6 — Agility training. (a) Slide board provides agility training for the lower extremity, and weight vest provides added resistance. (b) Inclusion of external resistance increases difficulty of the task.

Lunge exercises can be performed in different directions, beginning with body weight as resistance. When appropriate, the distal boundary condition can be altered so that the athlete is making contact with an unstable base. A minitramp can be used for this purpose. External perturbation forces can be applied in the form of sport cord tubing, and axial loading of the involved limb can be increased by applying a weight vest (Figures 7a and b). To further increase the complexity of the task, distracting stimuli can be incorporated into the movement pattern. The distracting stimuli can be in the form of activities that are specific to the athlete's sport.

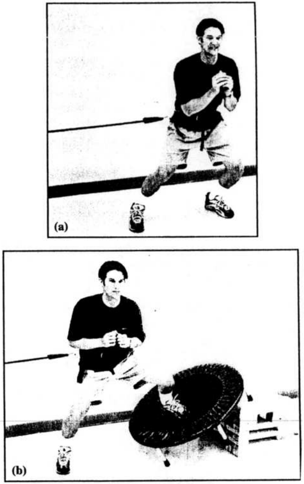

Figure 7 — Lunge (a) with external resistance and (b) with external resistance against an unstable distal boundary.

In order to progress to the late stage, outcome assessments should be performed to ensure that progression criteria have been met or exceeded. Selected performance-based and patient-report measures are used as in the early stage. We recommend that bilateral deficits not exceed 20% prior to late-stage progression.

Late Stage

In the late stage, plyometric, or stretch-shortening, exercise such as hopping and bounding movements is recommended to train the lower extremity muscles to respond quickly and forcefully. The ballistic nature of this exercise improves joint acceleration and deceleration movements. Eccentric loading is also emphasized in this stage.

Hopping protocols can begin with a double-limb take-off and landing technique and progress to a single-limb technique. The athlete can start by hopping in a single direction and progress to a multidirectional pattern in a preset or random orientation. Towel rolls or other similar objects can be added to increase hop height. Once lete has adapted to the exercise, external resistance can be added in the form of sport cord tubing or a weight vest (Figures 8a and b). Additionally, the distal boundary

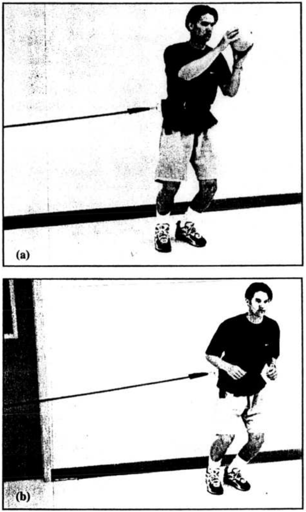

Figure 8 — Lateral bounding. (a) Lateral bounding over one foam roll with distract ing stimuli. (b) Sequence of bounds using two foam rolls against external resistance.

condition can be altered from a fixed, stable boundary to a fixed, unstable boundary. Soft foam can be used to create the unstable-boundary condition.

Bounding and depth-jumping exercises are considered high-impact, and we recommend instituting this type of exercise last. Bounding maneuvers can be performed initially using a double-limb technique, later progressing to a single-limb technique. Bounds can be performed in several directions (lateral, forward, or diagonal), in any sequence. A platform of varying height is used to increase the impact force and facilitate the concentric response. Initially, the athlete can adjust to the activity by performing only the landing, or eccentric phase, of the bound (Figure 9a) and later advance to a landing-jump technique. As stated earlier, the challenge of the task can be increased as needed by incorporating external perturbation forces, altering the boundary conditions, and adding a weight vest (Figure 9b).

Once the athlete demonstrates considerable progress and is comfortable with this exercise, a gradual scheme for return to full practice and competition must be implemented and carefully followed. Outcome assessments should be performed to ensure that the athlete is ready to return to practice and competition. Examples of performance-based measures include hop tests for distance and time, agility

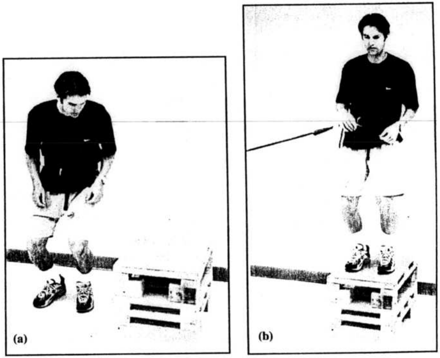

Figure 9 — Depth jumps. (a) Landing followed by (b) jumping back to platform with external resistance.

tests such as carioca and shuttle run, and patient-report measures. Bilateral deficits should be less than 10%.

Summary

Functional training for the purpose of restoring dynamic joint stability has received considerable interest in recent years. Contemporary functional training programs are being designed to complement, rather than replace, traditional rehabilitation protocols. We present a management strategy for restoring dynamic stability in the PCL-injured knee that integrates five key concepts: planned variation of exercise, outcomes-based assessment, kinetic chain exercise, proprioception and neuromuscular control, and specificity of activity. Once dynamic quadriceps function is established, the clinician should direct his or her focus to reestablishing proprioception and neuromuscular control. The rehabilitation should be progressive in nature and should address all sensory subsystems and levels of sensorimotor control. The long-term goal of functional training is a safe return to full function with minimal risk for reinjury. Transitional exercise should be integrated into the progression plan to provide a safe and gradual adjustment to the newly imposed demands. Progression criteria in the form of qualitative and quantitative data are recommended to ensure that treatment goals are being met.

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