Closed-Chain Rehabilitation for Upper and Lower Extremities

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Abstract

Closed-chain exercise protocols are used extensively in rehabilitation of knee injuries and are increasingly used in rehabilitation of shoulder injuries. They are felt to be preferable to other exercise programs in that they simulate normal physiologic and biomechanical functions, create little shear stress across injured or healing joints, and reproduce proprioceptive stimuli. Because of these advantages, they may be used early in rehabilitation and have been integral parts of "accelerated" rehabilitation programs. The authors review the important components of a closed-chain rehabilitation program and provide examples of specific exercises that are used for rehabilitation of knee and shoulder injuries.

Definitions

The human body produces motions and performs complex skills through sequential activation of muscles and movement of body segments, or links. This link activation, which may be activity- or sport-specific, is termed a "kinetic chain." There are two broad-based classes of kinetic chains—"open," in which the terminal link is not loaded and is freely movable (mobile end, no load [MNL]), and "closed," in which the terminal link is constrained or immovable due to a fixed position or large load (fixed end, external load [FEL]). The motion of the foot of a kicking leg is an example of an MNL kinetic chain. A pure FEL kinetic chain is exemplified by a fixed foot during a squat exercise. Force generation, force distribution, joint motion, muscle activation, and resultant tissue stress can be quite different in the two classes.

Orthopaedic surgeons are intimately involved in the rehabilitation process, in that they establish the anatomic diagnosis of the injury, determine the timing of entrance into and exit from the rehabilitation program, and select the modalities and exercises that are used. Even though they usually do not physically demonstrate or personally supervise the exercises, they must understand the basic concepts underlying the various types of exercises and the timing of exercise progressions, in order to effectively communicate with the physical therapists and coordinate the best program for the individual patient's needs.

Most current rehabilitation programs emphasize functional restoration of the injured part, which requires not only repair and healing of injured tissues but also restoration of correct positioning and movement of joints as well as activation of muscles in the proper sequence so as to achieve normal function. Closed-chain protocols have been advocated in rehabilitation because they have characteristics that encourage more complete functional restoration. These exercises have been used extensively for anterior cruciate ligament (ACL) injuries as a major component of "accelerated" knee rehabilitation, as well as for rehabilitation of patients with patellofemoral and shoulder injuries.

Despite increasing usage, there is still controversy about what closed-chain exercises are and how and when to use them. Neither is there a common understanding of what defines a closed-chain exercise, how closed-chain exercises promote functional restoration, and what the best closed-chain exercises are for different stages of the rehabilitation process. To be able to appropriately prescribe and utilize these techniques, the physician must first understand the underlying physiology and biomechanics of closed-chain rehabilitation.

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Steindler was the first to describe the differences in muscle activation and joint motion that occur when the distal end of the arm or leg in a kinetic chain meets considerable resistance compared with when it is freely movable. His definition of a closed-chain condition required that the foot or hand meet enough resistance to prohibit or restrain its free motion, and that the resultant extremity muscle activation was sequential from distal to proximal in the extremity.

Physical therapy protocols have been developed to take advantage of the force-generation and loading characteristics of closed-chain exercises. There has been wide variety in their application, but in general, closed-chain protocols include a progression of exercises that are based on application of a load to the distal end of an extremity that does not move freely due to either positioning (e.g., on a wall or on the ground [Fig. 1]) or the load characteristics (e.g., axially applied heavy load). Subsequent joint motion takes place in multiple planes while the limb is supporting weight. These conditions differentiate these exercises from “open chain” exercises, such as knee extensions, trunk extensions against gravity, and isolated rotator cuff exercises with tubing or weights.

Dillman et al. described conditions that define closed-chain exercises. They realized that the effect of the exercise on joint positions and muscle activations is the critical point in defining a closed-chain exercise. They felt that closed-chain exercises have to include relatively small joint movements, low joint accelerations, large resistance forces, joint compression, decreased joint shear, stimulation of joint proprioception, and enhanced dynamic stabilization through muscle coactivation. They also recognized that the amount of load at the terminal end of the extremity is as important as the motion of the extremity. Even if the distal end of the extremity is somewhat mobile, a large enough load can still create physiologic conditions that replicate closed-chain characteristics. This enlarged the concept of a closed-chain exercise from being only an FEL activity to include mobile end–external load (MEL) activities as well, making it more applicable to the upper extremity. For example, a military press (an MEL exercise) can have closed-chain effects similar to those of a pushup (an FEL exercise). This concept has been validated by Blackard et al. who found that there was no difference in muscle activation between equivalently loaded upper-extremity exercises with either fixed or mobile ends. They concluded that external loading characteristics were more important than arm motion in describing and simulating human activity.

Lephart and Henry modified the MEL condition to include two different external load conditions—axial load (e.g., military press) and rotary load (e.g., arm rotations with dumbbells). This helped to define types of exercises but did not change the concept that closed-chain joint loading and muscle activation characteristics can be obtained with a movable distal end. However, it enlarged the scope of the types of exercises that can be employed in a closed-chain rehabilitation program.

Livingston developed an operational definition to guide implementation of closed-chain exercises and to determine whether exercises have the characteristics described by Dillman et al. As Livingston defines closed-chain rehabilitation exercises, the activities require a sequential combination of joint motions; the distal end of the kinetic chain meets considerable resistance (MEL or FEL conditions); and movement of the individual joints of the kinetic chain sequence and translation of their instant centers of rotation occur in a predictable manner determined by the distribution of forces throughout the chain. This definition implies control by the physician or therapist of (1) extremity position, (2) distal segment motion and position, (3) application of forces and loads, and (4) movement of the entire extremity.

**Physiology and Biomechanics of Closed-Chain Rehabilitation**

Most lower-extremity occupational and athletic activities involve kinetic chain activity. The large majority of these activities start with the feet on the ground, which gives a base of stability, allows generation of a ground-reaction force, and initiates a sequence of segment activity to provide optimal position and motion for the distal aspect of the terminal segment in the chain. Force production is governed by the “summation of speed” principle, in
which the total energy or force in a kinetic chain is summated from the contributions of individual segments. Kinetic-chain segment motions and positions are created by muscle activation patterns. Length-dependent patterns operate locally around a joint, using co-contraction force couples to control joint perturbations. Force-dependent patterns harmonize segment motions by operating around two or more joints and using agonist-antagonist force couples to generate or transfer force. These two types of muscle activations result in coordinated segment motions that allow kinetic-chain activity to produce the desired forces needed for occupational or athletic purposes. The resultant synergistic patterns create postural stability throughout the entire extremity while allowing voluntary muscle activity at the distal segment. These synergistic patterns include increased activation of biarticular muscles (i.e., gluteus medius, soleus, and coordination of arm and scapular movements to produce glenohumeral stability through the range of motion, allowing maximum arm motion). They are highly dependent on joint- and angle-specific proprioceptive feedback.

In the leg, the hamstrings act as part of a length-dependent force couple to control anterior tibial translation. They also work as part of a force-dependent pattern to coordinate hip and knee motion, stabilize the hip, and transfer loads up and down the leg. In the shoulder, the rotator cuff acts as part of a length-dependent force couple to increase glenohumeral concavity and compression, but also works as part of a force-dependent pattern to link trunk extension, scapular rotation, and arm internal rotation.

Closed-chain exercise protocols have characteristics that simulate these biomechanical and physiological requirements. Mechanically, they initiate joint movements from the ground or a base of support, emphasize sequential control of segment position or motion, place the segments in functionally correct positions, and control the transfer of generated loads. Physiologically, they utilize both length-dependent and activity-specific force-dependent activation patterns, emphasize position-specific proprioceptive feedback to initiate and control activation, and can use the more versatile MEL configuration to achieve FEL muscle activation (Fig. 2).

Closed-chain exercises have also been shown to be protective for healing and repaired tissues. They produce minimal translation, shear, and distraction forces due to the compressive nature of the applied load and the greater control of the resultant motions. This confers a margin of safety that allows shorter periods of complete immobilization, earlier initiation of rehabilitation, and resultant “accelerated” protocols.

Because closed-chain exercises emphasize and produce patterns of

Figure 2 Intermediate-stage lower-extremity exercises. A, Use of a sliding board for an MEL exercise to balance the body over a moving leg. The patient slides side to side and pushes off each edge. B, Use of a Fitter involves the same principles as use of a sliding board, but there is a more unstable base due to its rounded edges, therefore presenting more of a proprioceptive challenge.
motions and muscle activations, they may not maximally rehabilitate all of the individual muscles or achieve normal motion of all of the joints in the relevant kinetic chain. This is due to both muscle-activation substitutions and alterations that allow approximations of the normal patterns and to individual characteristics of muscle activation. Some muscles, such as the deltoid, upper trapezius, gluteus medius, and gastrocnemius, are more resistant to inhibition and alteration in injury or fatigue situations; others, such as the serratus anterior, lower trapezius, supraspinatus, and vastus medialis obliquis (VMO), are easily fatigued and inhibited, and tend to “drop out” from the activation patterns.

Clinical examples of these alterations include hip abductors and extensors substituting for knee extension in gait after ACL reconstruction, the upper trapezius substituting for the lower trapezius in acromial elevation, and the deltoid substituting for the supraspinatus in arm elevation. In these situations, the desired kinetic-chain function (walking or arm elevation) may be accomplished, but activation of important muscles is not. Rehabilitation strategies can be developed to maximize activation of the inhibited muscles while still utilizing a closed-chain framework. This involves placing the extremity in a closed-chain position, emphasizing the normal activation pattern, and progressively “unmasking” the target muscle by eliminating the substituting muscle. This process may be called “facilitation of muscle activation.”

Role of Closed-Chain Exercises in Rehabilitation

Closed-chain rehabilitation protocols have beneficial characteristics that are associated with functional physiology and biomechanics. They may be utilized early in the rehabilitation sequence to protect the injured area and to prepare the entire kinetic chain for function. They are the foundation for some rehabilitation programs. However, they must be monitored to ensure that all muscles are being appropriately activated. These protocols can be used in both MEL and FEL configurations for knee and shoulder rehabilitation (Figs. 3-7). Different levels of exercises may be used in the early (acute or healing) phase, the intermediate (recovery) phase, and the late (functional) phase of rehabilitation depending on the degree of tissue healing, the possible positions of the extremity, and the amount of load and the range of motion that are allowed.

Knee and Leg Rehabilitation

Closed-chain rehabilitation techniques have been utilized to accelerate and improve functional restoration after ACL injury and reconstruction. These techniques create weight-bearing forces across the joint that increase local agonist-antagonist muscle coactivation, decrease joint shear, minimize joint displacement and ACL strain, and reproduce proprioceptive stimuli. In addition, they activate the kinetic chains of weight bearing, running, and jumping. This reproduces the normal biomechanics of the entire leg, allowing hip-muscle activation to increase quadriceps and hamstring force output by transferring muscle work to these biarticular muscles and by creating a hip moment that is a major contributor to the knee moment. Hip-muscle activation and work output create load-absorbing capacity that can compensate for a low load-absorbing capacity in the knee so that the entire leg functions at an acceptable level early in rehabilitation. Closed-chain exercises also reproduce the physiologic length-dependent patterns for hip- and knee-joint stability, as well as force-dependent patterns of coordination of hip, knee, and ankle joint motion. The effect that closed-chain exercises have on the entire kinetic chain is more functionally important than the effect on the knee joint alone.

Closed-chain techniques are also useful in rehabilitation of the patient with patellofemoral pain, largely due to the same factors of joint position control, larger improvements in the strength of the entire kinetic chain, and alteration of the magnitude and position of applied forces. Increased total leg stiffness, with resultant knee joint control, is achieved by activating the hip muscles concurrently with the knee muscles. Closed-chain exercises have been shown to produce greater improvements in quadriceps strength and leg performance than open-chain exercises.

Lower-extremity closed-chain exercises are largely FEL, with the foot on the ground in the early rehabilitation stages. Most protocols emphasize early, if not immediate, weight bearing on the affected extremity. The leg may be supported, but controlled range of motion and compression loading of the joint are encouraged. Initially, the patient is in a two-legged support stance, but may be moved into a one-legged support stance as healing progresses. Rhythmic motion patterns of flexion/extension and lateral movement are used. Early emphasis is placed on achievement and maintenance of a position of 0 degrees of hip extension and neutral pelvic tilt to allow maximum hip-muscle activation. Most leg exercises should proceed from this “ideal” position.

Closed chain–based protocols advocated for rehabilitation of ACL and patellofemoral injuries.
are similar in their early stages, but differ in the intermediate and recovery stages (from 3 weeks to 3 months). Common characteristics include progressive compression loading of the joint, controlled increase in range of motion, maintenance of functional posture of the knee and leg, and emphasis on early return to functional activities, such as running, weight lifting, and mild cutting.

Some of the more commonly advocated closed-chain exercises in the intermediate and recovery stages include the two-legged squat with increasing resistance, the one-legged squat with support, and the step up–step down maneuver—all of which are FEL exercises. Examples of MEL exercises include slid-
In the late stage (after 3 months), emphasis is on functional progressions and a mixture of closed- and open-chain exercises. The closed-chain exercises for joint coordination, leg control, and resistance to perturbation should be regarded as a base for the open-chain exercises of jumping rope, cutting, kicking, leg extensions, and leg curls.

Facilitation patterns to maximize quadriceps activation and increase knee load-bearing capacity are also employed in the recovery and functional stages of rehabilitation. They initially involve active hip extension and quadriceps activation with the foot flat on the floor or stepping off a flat step (Fig. 3, A and B). This FEL pattern reactivates the normal sequencing pattern for the entire leg, but probably does not maximally isolate or activate the quadriceps. The MEL equivalent, using a trampoline, wobble board, or Fitter, adds an element of increased proprioceptive feedback. More effective quadriceps activation in a closed-chain exercise is accomplished by placing the foot on a slant board. Ankle plantar-flexion and slight hip flexion decrease hip and ankle activation, but slight knee flexion places more emphasis on quadriceps activation as the patient executes a step up–step down maneuver (Fig. 3, C). Further quadriceps facilitation is accomplished by one-legged stance, hip extension, slight knee flexion, and hip and trunk rotation around the planted leg (Fig. 3, D and E). This FEL exercise promotes maximal electromyographic activity in the VMO. The MEL equivalent utilizes a trampoline or wobble board.

In summary, closed-chain exercises for knee rehabilitation allow early weight bearing, protect the injured or healing area, and prepare the entire extremity for vigorous functional open- or closed-chain athletic activities. They should form the basis for most knee rehabilitation protocols, including those for ACL and patellofemoral injuries. The exact sequence and composition of the protocols may be variable, but limited outcomes assessments indicate a faster return to functional status with protocols in which these types of exercises are emphasized.

Shoulder and Scapular Rehabilitation

On superficial analysis, it would appear that closed-chain rehabilitation would have little application for the shoulder and arm. The hand is
obviously moving in an open-chain fashion in throwing and serving, and the arm assumes a weight-bearing position only in gymnastics and blocking in football. However, shoulder position, motion, and force transfer fit the physiologic and biomechanical requirements of closed-chain activities. In throwing and serving, the scapula and shoulder display intersegmental coordination, with coupled movements that are predictable on the basis of arm position.\textsuperscript{[8,10]} The shoulder acts as a stable funnel, transferring and regulating forces in the kinetic chain from the legs to the hand.\textsuperscript{[1,20]} The shoulder muscles are activated in mainly co-contraction length-dependent patterns to stabilize the joint.\textsuperscript{[9,10,20,21]} Proprioception plays a major role in controlling and activating muscle patterns.\textsuperscript{[11]} In swimming, weight lifting, and playing on the offensive or defensive line in football, the hand meets considerable resistance but still moves, creating MEL conditions at the distal end of the extremity.

Closed-chain exercises should, therefore, be utilized in shoulder and scapula rehabilitation for functional return to most athletic activities from all types of shoulder injuries. Rehabilitation protocols for tendinitis, postoperative instability, and postoperative labral injuries are basically the same in the acute phase and in the early functional phase.\textsuperscript{[5,7]} Postoperative rotator cuff protocols should vary with the integrity of the repair, but can also benefit from the proximal activation and low shear characteristics. Just as in knee and leg rehabilitation, closed-chain exercises may be used in the early stages of rehabilitation, and emphasis should be placed on involving all of the joints of the kinetic chain.

Early-stage exercises involve not only the scapula but also the hip and trunk. The large extrinsic muscles of the shoulder (the latissimus dorsi and pectoralis major) and the muscles that position the scapula (the upper and lower trapezius and serratus anterior) are all attached to the trunk. They provide key stability and force generation to decrease shoulder load and facilitate rotator cuff activation. Early in rehabilitation, when the shoulder muscles are weakest, facilitation needs from proximal muscle activation are at their greatest. Muscle activation patterns to rehabilitate these muscles start with stabilization of the hip and trunk, and involve diagonal as well as ipsilateral exercises. Diagonal activations (from left hip to right arm and from right hip to left arm) are important to recreate the rotational activation and control patterns that are used in athletic activities such as throwing and swimming and in daily activities such as reaching and starting a lawn mower. Commonly employed exercises to rehabilitate these patterns include trunk extension–scapular retraction (Fig. 4, A) and diagonal hip extension–scapular retraction (Fig. 4, B). These exercises may be done both preoperatively and in the immediately postoperative period. They involve minimal forces at the shoulder and may be done with the arm in a sling or other protective device. Such exercises create a stable posture of the proximal segments that allows accelerated rehabilitation of the healing distal tissues.

Closed-chain exercises are the most effective method for rehabilitation of the patient with scapular dyskinesis (alterations in scapular...