Incorporating the Squat Exercise in the Rehabilitation of the Reconstructed Anterior Cruciate Ligament Knee

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The Kinetic Chain of the Body  
The concept of the Kinetic Chain has been referred to by mechanical engineers as a link system. This link system has been described as a series of overlapping, rigid segments which are connected by pin joints. If both ends of this system are fixed to an immovable frame, translations at both the proximal and/or distal ends are impossible. Movement of one joint in this system allows for predictable movement at all other joints included in the same system. However, this type of closed link system does not exist in the extremities of the human body during normal function.

Documentation of the kinetic chain of the body can be found as far back as 1955. Dr. Arthur Steindler described the kinetic chain of the body in his textbook of kinesiology as a "combination of several successively arranged joints constituting a motor complex." He proposed that the extremities could be thought of as a series of rigid, overlapping segments. Although this type of closed kinetic chain does not exist during functional activities, two different types of kinetic chain do exist under different limb loading conditions. Dr. Steindler felt that these differences in loading conditions warranted separate descriptive terminology. He described an open kinetic chain (OKC) as a combination of successively arranged joints in which the terminal joint is free to movement. He also defined a closed kinetic chain (CKC) as "one in which the terminal joint meets with some considerable resistance which prohibits or restrains its free motion". It is important to note that muscle recruitment patterns and joint movements are different when the distal segment of an extremity is fixed (CKC) versus one that is allowed to move freely (OKC). A true closed kinetic chain of the body can only exist in an extremity during the performance of an isometric exercise. This type of exercise provides no movement at either the proximal or distal segments of the extremity, thereby allowing for a true closed chain system. However, this type of exercise is not specific to dynamic human function.

Kinetic Chain Rehabilitation Training  
Appropriate exercise selection is essential during the rehabilitation of the reconstructed anterior cruciate ligament (ACL) patient. The rehabilitation specialist should be familiar with normal knee biomechanics, as well as the biomechanics of the knee during the performance of specific rehabilitative exercises. This will familiarize the therapist with the stresses placed on the ACL graft during the performance of these exercises. Collagen fibers of the ACL are thought to fail at only 10% to 15% elongation by serial tearing in the ascending portion of the loading curve. This serial tearing may lead to further gross graft disruption. Excessive strain during rehabilitative exercise may stretch the healing graft to the extent that the reconstructed ligament may be non-functional although the graft is still intact. Proper protection of the graft is vital, especially during the initial stages of the rehabilitation process.

The Biomechanics of Closed vs. Open Kinetic Chain Exercise  
Biomechanical considerations during the rehabilitation of the ACL reconstructed knee include the relative amount of anterior-posterior tibial translation and shear forces that occur during the performance of OKC and CKC exercise. The primary anatomical restraints during OKC exercise include the cruciate ligaments, menisci, and soft tissue structures of the knee. CKC exercises utilize these restraining structures as well as osseous knee joint geometry and compressive loads.

Jurist and Otis measured the effect of isokinetic dynamometer pad placement at fixed flexion angles on anterior-posterior knee translation. Proximal pad placement resulted in posterior tibial translations at 30, 60 and 90 degrees of knee flexion while distal pad placement resulted in anterior tibial translations at 60 and 30 degrees of knee flexion. In cadaveric studies, Grood et al reported that anterior translation of the tibia on the femur occurred throughout most of the range of motion (ROM) when the leg was extended against gravity. It was demonstrated that the ACL was loaded in the last 30 degrees of extension, and that large quadriceps forces were required to accomplish the last 15 degrees of knee extension. These forces were typically twice those that were necessary to achieve 30 degrees of knee flexion. The addition of weights increased these
quadriceps forces and concurrent patello-femoral and tibio-femoral contact forces. Lutz\textsuperscript{10,11} has reported a decrease in tibio-femoral\textsuperscript{10} and patello-femoral\textsuperscript{11} shear forces at the knee during CKC exercises as compared to OKC exercises. These reduced shear forces are a result of a more axial orientation of the applied force of CKC exercise, as well as the phenomenon of muscular co-contraction of the quadriceps and hamstring muscle groups. Henning et al\textsuperscript{7} reported \textit{in vivo} increased ACL elongation during OKC activities such as leg raises at 22 degrees of knee flexion with a 20 pound weight. The authors discovered that single leg squatting produced less elongation than not only OKC activities, but also less elongation than the standard Lachman and pivot shift tests used commonly as part of the orthopedic knee evaluation. Henning further recommended that full ROM knee extension exercise not be performed during the first year following ACL injury or reconstruction.

Yack et al\textsuperscript{22} found significantly greater anterior tibial displacements during knee extension exercise in the 64 degree to 10 degree knee flexion ROM as compared to the squat exercise in the ACL deficient knee. His findings were similar to those of Dr. Henning in that anterior tibial translations of the knee were also significantly greater during the performance of a Lachman test when compared to the anterior tibial translation which occurred during squat exercise.

Increases in immediate post-exercise knee translation have been documented following specific activities such as bicycle ergometry, Cybex training, distance running, downhill skiing, and basketball playing\textsuperscript{5,16,17}, but powerlifters who squatted were the only group of athletes that did not demonstrate an increase in knee translation immediately following activity.\textsuperscript{17}

Squat exercises performed by college aged subjects and professional football players over an eight and twenty-one week period respectively, did not demonstrate any detrimental effect on knee joint stability.\textsuperscript{1,14}

THE SQUAT EXERCISE
By definition, the squat exercise is a CKC activity. The use of this exercise has been advocated by weightlifters, body builders, strength coaches, and athletes to enhance both physique and athletic performance. In fact, this exercise has been deemed "the king of exercises"\textsuperscript{13} and considered by many to be the cornerstone for the development of athletic performance.\textsuperscript{1,13,15} Performance of this exercise requires a synchronous contribution of the three main links (hip, knee, ankle) of the lower extremity kinetic chain. Also incorporated during the exercise performance are the components of balance, coordination, proprioception, and both concentric, and eccentric muscle training.

PERFORMING THE SQUAT EXERCISE
The squat exercise is performed in the standing position with the feet placed approximately shoulder width apart and externally rotated 10 to 15 degrees. The amount of rotation will depend upon patient comfort. This external rotation of the lower extremity is an attempt to replicate the screw home mechanism of the knee in the position of full extension. A barbell of a specific weight is placed upon the patient's shoulders (\textbf{Figure 1}). Keeping the back as erect as possible, the patient descends toward the ground until the knees achieve a flexion angle of greater than 90 degrees, this position is termed a full squat (\textbf{Figure 2}). During the descent, special care is taken to keep the forward movement of the knees behind the toes in an attempt to keep the anterior shear forces across the tibio-femoral joint to a minimum.\textsuperscript{1} The exercise is concluded by having the patient return to the starting standing position (\textbf{Figure 1}).

\textbf{Figure 1}
\textit{The Squat Exercise Starting Position}
This exercise requires the patient to maintain a consistent speed of descent and ascent from the start to the completion of the exercise. It has been reported\(^1\)\(^2\) that less skilled national caliber powerlifters demonstrated a larger initial body (bar) velocity at the start of the exercise, and maintained this increased velocity throughout the descent. Just prior to the completion of the descent, the less skilled powerlifters more sharply reduced the body's velocity than the high skilled powerlifters. This resulted in a "bounce" condition during the period of transition from descent to ascent in the full squat position (Figure 2). This "bounce" condition has been shown to increase the shear forces at the knee during the performance of the squat exercise.\(^1\)

When initially incorporating the squat exercise in the rehabilitation program, many patients may not have the ability to perform a full squat or barbell squat exercise. Initially mini-squats may be incorporated with the use of the patient's body weight. A progression is made by having the patient hold dumbbells at their side initially, and a further progression is made by holding the dumbbells at the level of the shoulders (Figure 3). As the patient adapts comfortably to the exercise, attempts may be made to increase the depth of the descent until a full squat position is achieved. The progression is continued until the patient can perform a full squat with the use of a barbell. It is important to note that each patient should be treated as an individual and differences in the type (variation) of squat performed, its depth, and the amount of weight lifted will be based on these individual differences.
HE ROLE OF THE TRUNK DURING SQUAT EXERCISE PERFORMANCE

A major advantage of the squat exercise is that it incorporates the use of the entire body during the performance of the exercise. This is especially true of the trunk of the body, and more specifically, the musculature of the low back. McLaughlin has reported that during the final position of the descent, the less skilled athlete will demonstrate a body position of greater forward flexion of the trunk as the hips move a greater distance horizontally backward when compared to higher skilled athletes. During the initial period of ascent from the full squat position, body (bar) velocity increases to a peak value and then decreases to a minimum velocity at approximately 60 degrees of knee flexion (Figure 4). Less skilled athletes will reach this position with "lower hip and bar velocity and greater forward lean".  

The increased trunk flexion positions described above may expose the patient to increased stress to the lower back musculature and possible back injury. This may also contribute to failure of exercise performance due to poor technique. It is therefore extremely important to incorporate trunk strengthening and flexibility exercises, with the emphasis placed on the low back and abdominal musculature as part of a patient's ACL rehabilitation program. This will assist the patient in maintaining a more erect posture thereby reducing the stress placed on the low back while reinforcing proper exercise technique for successful squat performance.

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