THE EFFECTIVENESS OF PROPRIOCEPTIVE TRAINING IN THE ACL
RECONSTRUCTED KNEE

by

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ABSTRACT

Purpose

The main purpose of this study was to determine the effectiveness of proprioceptive training in the ACL reconstructed limb. The second purpose of this study was to determine the relative contribution of isokinetic strength and peak hamstring torque time to functional ability.

Methods

Ten subjects with unilateral ACL reconstructed limbs were randomly assigned to two experimental groups. Group One (Strength Training Group) consisted of five subjects who were placed on a 12 week general lower body strength training program. Group Two (Proprioceptive Group) consisted of five subjects who were placed on a 12 week proprioceptive training program for the lower extremities. Peak hamstring torque time (PTT) was measured using the protocol described by Small et al.¹. Average concentric and eccentric torques of the quadriceps and hamstring muscles were measured using the KIN-COM isokinetic dynamometer. Functional ability was determined by the one-legged single hop for distance (SLHD) and the one-legged timed hop. Subjective scores were obtained from the Lysholm and Gillquist Knee Scoring Scale and the Tegner and Lysholm Activity Scale.

Results

Both training protocols were found to influence peak hamstring torque time of the ACL reconstructed limb. No significant differences were found between or within the two experimental groups. However, a group by test occasion interaction effect on peak hamstring torque time was found. A curvilinear relationship between PTT and test occasion was evident for both experimental groups. The strength training group demonstrated a slowing of PTT at 6 weeks, while the proprioceptive training group demonstrated an improvement in PTT at 6 weeks. At the end of the 12 weeks, both experimental groups regressed toward their baseline PTT values, such as the strength training group demonstrated an improvement in PTT while the proprioceptive training group demonstrated a slowing of PTT in the latter six weeks.

There was a significant group by test occasion interaction effect on isokinetic strength measures. The proprioceptive group demonstrated greater isokinetic strength gains than the strength training group after 12 weeks of training. Both experimental groups demonstrated similar significant gains in functional ability. Both groups also demonstrated similar significant gains in the subjective assessment (Lysholm and Gillquist Knee Scoring Scale) and the subjective analysis of physical function (Tegner and Lysholm Activity Scale) after 12 weeks of training.

Regression analyses indicated isokinetic strength of the quadriceps and the hamstring muscles to have significant effects on functional ability (SLHD). Average concentric hamstring torque was found to have the most significant effect on functional ability.

Conclusion

Both strength training and proprioceptive training have an influence on peak torque time. It is proposed that the two types of training influence PTT through different neuromuscular mechanisms. Strength training is proposed to positively influence PTT by increasing fast twitch/slow twitch (FT/ST) muscle area ratio and to negatively influence PTT by decreasing muscle spindle sensitivity. Proprioceptive training is proposed to positively influence PTT by improving coordination and neural activation of the appropriate muscles. Coordination relies on proprioception and kinesthesia. However, the effectiveness of proprioceptive training is dependent on appropriate progression and repetition. Early integration of speed, force, and complexity of movement into proprioceptive training may decrease the effectiveness of training. Thus, the integration of these components should only occur if precision of performing motor tasks is not compromised.

Both strength training and proprioceptive training may have beneficial effects on subjective scores and functional ability. Greater isokinetic strength gains can be observed with proprioceptive training than with strength training as training occurs over time. These greater isokinetic strength gains are proposed to be secondary to improved muscle coordination and neural activation rather than actual muscular hypertrophy.

The strength of the lower extremities contribute significantly to functional ability. The strength of the hamstring muscle appear to play a greater role in functional ability than the quadriceps.

However, due to the small sample size used in this study, the ability to generalize these results may be limited.

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Chapter One

INTRODUCTION

The anterior cruciate ligament (ACL) is the most commonly ruptured ligament in the human knee joint.² It is estimated that half a million people in the United States sustain a clinically significant ACL injury annually.³

The ACL plays a major role in maintaining the normal function of the knee. Like all ligaments, the ACL guides joint motion by preventing unphysiologic and excessive motions.³ In addition, it works in partnership with the muscles and articular surfaces to transmit the loads of activity across the joint. Once the integrity of the ACL is disrupted, a reduction in functional ability and stability of the affected knee is often seen. Despite all the information to date on the ACL, the understanding of its structure, function, and biology is not to the point where the ligament can be restored to its pre-injury state. Numerous studies have proposed that one of the possible factors limiting the ACL reconstructed or ACL deficient limb from achieving pre-injury status is altered proprioception. It is believed that injury to the ACL results in altered somatosensory information that adversely affects motor control. This may subsequently lead to an increase risk for recurrent injury, decreased performance, or both.

Histologically, it has been demonstrated that the human ACL contains mechanoreceptors that can detect changes in tension, speed, acceleration, direction of movement, and the position of the knee joint.^{4, 5} Currently, proprioceptive training following an ACL injury is emphasized in the attempt to maximize the sensory information mediated by the joint and musculotendinous afferents to dynamically stabilize the joint.⁶ Although diminished or altered proprioception and kinesthesia have been documented after ACL injuries, very few prospective studies have examined the effectiveness of proprioceptive training after ACL injuries. Of those prospective studies found in the literature, none involved the ACL reconstructed population.

The main purpose of this study was to determine the effectiveness of a proprioceptive training protocol versus a strength training protocol in restoring the neuromuscular function of the ACL reconstructed limb.

The second purpose of this study was to determine the relative contribution of isokinetic strength and peak hamstring torque time to functional ability.

LITERATURE REVIEW

Embryology of the ACL

The appendicular skeleton consisting of the pectoral and pelvic girdles plus the bones of the upper and lower limbs appears quite early in the embryologic process.⁷ The limbs begin to appear as small elevations from a slight lateral ridge extending along each side of the trunk.⁸ The forelimb buds show first, at the level of the more caudal cervical segments and the hind-limb buds are level with the lumbar and upper sacral segments. Although the upper limbs appear earlier in utero and are relatively more mature, the lower extremities develop more rapidly than the upper extremities at birth and throughout the early neonatal growth.⁷

The development of the knee joint can first be detected in the fourth week of development, or the 5 mm stage of human embryo, from a concentration of mesenchyme.⁷ The development of the knee joint is quite rapid, and by six weeks, a very obvious knee joint is discernible.

The cruciate ligaments of the human knee joint first appear as condensations of vascular synovial mesenchyme (in the blastoma) at about 6.5 weeks of development, well before joint cavitation occurs, and remains extrasynovial at all times.^{3, 7} The ACL begins as a ventral ligament and gradually invaginates with the formation of the intercondylar space. From its earliest appearance, the ACL changes very little to achieve its final form.⁷

By ten weeks, the ACL and the posterior cruciate ligament (PCL) are separate from each other and are easily distinguished from one another by the direction of their parallel fibers.³ By the twentieth week of development, the cruciate ligaments resemble those of the adult.³

Gross Anatomy of the ACL

The ACL is intra-articular but is extrasynovial within its synovial envelope.⁹ Proximally, it attaches to the posterior aspect of the intercondylar surface of the lateral femoral condyle.^{7, 9, 10} The femoral attachment is shaped like a segment of a circle, with its anterior border straight and its posterior border convex.⁹ The femoral attachment covers an area of approximately 2 cm².⁷ Distally, the ACL attaches anteriorly and laterally to the tibial spine. Portions of the anterior fascicles of the ligament occasionally will blend with the anterior horn of the lateral meniscus. On rare instances, the posterior fascicles will blend with the posterior horn of the lateral meniscus.⁹ The tibial attachment has a surface area of approximately 3 cm².⁷ The tibial insertion of the ACL is both larger and stronger than its femoral origin.

It has been observed that the insertion sites of the ACL pass through a transition zone before inserting into the bone.^{3, 11} The abrupt change from flexible ligamentous tissue to rigid bone is mediated through this zone of fibrocartilage and mineralized fibrocartilage, allowing a graduated change in stiffness and a reduction in stress concentration at the attachment sites. The transition zone is divided into four morphologically distinct zones:

1. Zone one is the ligament substance.
2. Zone two represents a region of fibrocartilage.
3. Zone three represents mineralized fibrocartilage.
4. Zone four is bone.

Due to the orientation of its bony attachments, the ACL is a three-dimensional fan-shaped structure that runs anteriorly, medially, and distally across the joint from the femur to the tibia.¹⁰ As the ACL courses through the knee joint, it turns on itself in a slight outward (lateral) spiral.⁹ On average, the ACL is 40 mm in length, 10 mm in width, and 5 mm in thickness.^{7, 10} The ACL is divided into the anteromedial, the intermediate, and the posterolateral bands (Figure 2.1).¹²

Figure 2.1¹²

The Tripartite Area of Origin.

(AM = Anteromedial, I = intermediate, PL = posterolateral)

The anteromedial band is composed of the fascicles arising from the most anterior portion of the tibial attachment and inserting on the most medial and proximal portions of the femoral attachment.¹² The posterolateral band is composed of the fascicles arising from the posterior portion of the tibial attachment and inserting on the most lateral and distal parts of the femoral attachment. All fascicles of the ACL are taut during the final 30° of knee extension.¹² The fascicles of the anteromedial band are taut principally in flexion while the posterolateral band becomes progressively taut as knee extension occurs. While this designation provides a general scheme as to the dynamics of the ACL throughout the arc of motion, one should keep in mind it tends to oversimplify somewhat. For even though the fascicles of the ligament are summarily divided into three bands, the ACL is actually a continuum of fascicles that provides stability in any position of the knee joint.¹²

Microanatomy of the ACL

The ACL is composed of multiple fascicles of collagen tissue.^{9, 10} The smallest structural unit is the fibril, 150 nm to 250 nm in diameter, which is grouped together to form fibers of 1 μm to 20 μm in diameter. Groups of fibers then form the subfascicular units, 100 μm to 250 μm in diameter, surrounded by an endotendineum. Three to twenty subfascicular units group together to make up a fasciculus, which may range from 250 μm to several millimeters in diameter. The fasciculus is surrounded by an epitendineum and the entire group of fascicles form the ACL that is surrounded by the paratenon.

In a study using dogs, humans, and rabbits, Clark and Sidles¹³ challenges the details of the organizational pattern mentioned above. Clark and Sidles¹³ observed only two distinct orders segmentation. The ACL was found to be composed of multiple 20 μm width collagen fiber bundles separated by a network of fine fibrils and cells. The bundles then group into fascicles that vary in size from 20 to 400 μm in diameter.

Vascular Supply of the ACL

The ligamentous branches of the middle genicular artery and the branches of the inferior genicular arteries provide the blood supply to the ACL.¹⁴ These blood vessels richly endow the synovial fold that covers the ACL and form a “web-like network of periligamentous vessels that ensheath the entire ligament.”¹⁴ The synovial fold covering originates from the posterior inlet of the intercondylar notch and extends to the tibial insertion of the ligament, where it joins the synovial tissue of the joint capsule distal to the infrapatellar fat pad. The middle genicular artery enters the upper one third of the ACL and its vascular branches course both proximally and distally along the ligament. The inferior medial and lateral genicular arteries enter the ACL through the medial and lateral fat pads respectively. Smaller connecting branches, derived from the periligamentous vessels, penetrate the ACL transversely and anastomose with a network of endoligamentous vessels.^{3, 14} These vessels, along with their supporting connective tissues, are oriented in a longitudinal direction and run parallel to the collagen bundles within the ligament. Minimal blood supply is derived from the ligamentous osseous junctions of the ACL.^{3, 14}

Neuroanatomy of the ACL

Nerve Supply of the Knee Joint

According to Kennedy⁴, there are two distinct groups of articular nerves for the knee joint. The posterior group consists of the prominent posterior articular nerve, which is a branch of the tibial nerve, and the terminal branch of the obturator nerve. The anterior group consists of articular branches of the femoral, common peroneal, and saphenous nerves.

Kennedy⁴ found the largest and most prominent nerve to be the posterior articular nerve. The posterior articular nerve branches from the posterior tibial nerve above the knee in the popliteal fossa. It then wraps around the popliteal vein and artery before it becomes the popliteal plexus, which penetrates the posterior capsule of the knee joint. Branches of this plexus supplies the posterior capsule, the posterior fat pads, the posterior oblique ligament, the medial and lateral ligaments (MCL, LCL), the PCL, the ACL, and the posterior parts of the annular ligaments surrounding the lateral and medial menisci.

The medial articular nerve is a branch of the saphenous and/or the obturator nerves, and it appears to be distributed to the medial and anteromedial aspect of the fibrous capsule, the MCL, the medial meniscus, the patella ligament, the infrapatellar fat pad, and the medial part of the patellar periosteum.

The lateral articular nerve takes a recurrent course after branching from the common peroneal nerve and innervates the capsule of the superior tibiofibular joint, the inferolateral tissues of the knee joint, and the peroneal muscles.

Innervation of the ACL

The ACL is innervated by the posterior articular nerve.⁴ Branches of the posterior articular nerve that innervate the ACL course along the periligamentous and endoligamentous vessels, where some of the nerves ramify and send nerve fibers into the collagenous substance of the ACL.

Recent morphologic and physiologic investigations have convincingly demonstrated that the ACL contains complex mechanoreceptors of different types that probably make significant contributions to motor control and proprioception. The

presence of mechanoreceptors within the ACL has been identified by a number of histological studies.^{4, 5, 15, 16}

Kennedy⁴ found neural elements similar to Golgi tendon organs within multiple clefts in the tibial origin of the ACL and in its richly vascularized synovial covering. Similarly, Schultz et al.¹⁶ found fusiform corpuscles resembling Golgi tendon organs at the surface of each cruciate ligament beneath the synovial membrane. More recently, Schutte et al.⁵ identified three morphologically distinct mechanoreceptors in the ACL:

1. Two types of Ruffini end-organs.
2. Pacinian corpuscles.
3. Free nerve endings.

Schutte et al.⁵ concluded that the specialized receptors and free nerve endings within the ACL constitute 1% of the area of the ACL while Zimny et al.¹⁵ suggested that they compromise 2.5% of the area.

Mechanoreceptors located in joint capsules and ligaments are thought to serve at least two major functions.^{17, 18} One, they provide important sensory feedback necessary for proprioception and kinesthesia. Two, they play a role in the initiation and coordination of appropriate muscle firing patterns, or reflexes, to stabilize the knee joint during functional activities. The exact mechanism by which muscular reflexes are initiated by mechanoreceptor feedback is a subject of debate.

Mechanoreceptors are found in the ACL as well as the PCL, medial and lateral collateral ligaments, menisci, patellar tendon, and infrapatellar fat pad.^{6, 19, 20}

Joint afferents are traditionally classified into four different groups according to their fiber diameter and conduction velocities.²¹ The four groups are:

1. Group I afferents have diameters from 10-18 μm and conduction velocities greater than 60m/s.
2. Group II afferents have diameters from 5-12 μm and conduction velocities of 20-70 m/s.
3. Group III afferents have diameters from 1-7 μm and conduction velocities of 2.5-30 m/s.

4. Group IV afferents have conduction velocities less than 2.5 m/s.

Group I fibers emanate from Golgi tendon organlike endings. The Group II fibers originate from the Pacinian corpuscles and Ruffini endings. Group III and IV myelinated and unmyelinated afferents originate from free nerve endings.²¹

Mechanoreceptors can be divided into four types:⁵

1. Type I mechanoreceptors are Ruffini-like receptors.
2. Type II mechanoreceptors are Pacinian-like receptors.
3. Type III mechanoreceptors are similar to Golgi tendon organs.
4. Type IV mechanoreceptors are free nerve endings that convey pain.

Fast adapting mechanoreceptors are the most sensitive indicator of change in the tension of the ligament.⁵ They identify acceleration at the initiation and termination of movement. Slow adapting mechanoreceptors are capable of continuous activity that can be quantitatively altered in response to variation in the tension of the ligament. These receptors identify motion, position, and angle of motion.⁵

Ruffini end-organs (Figure 2.2) are mechanoreceptors that have a very low threshold and respond to slight changes in tension within the ligament.⁵ They are capable of a prolonged discharge due to their slow adaptation, and therefore, play a role in conveying the proximity of the joint to its limit of motion in flexion and extension.⁶

The second morphologically distinct Ruffini end-organ identified in the ACL by Schutte et al⁵ resembled a Golgi tendon organ (Figure 2.2). Golgi tendon organs are also characterized by slow adaptation but have a high threshold for excitation. They respond at the extremes of motion and may be responsible for mediating protective reflex arcs.⁶ Ruffini end-organs and Golgi tendon organs have been described as the dominant receptor types in joint capsules.²²

The Pacinian corpuscle (Figure 2.2) is a fast adapting mechanoreceptor that is activated by movements of the knee joint, regardless of position.⁵ These receptors have a low threshold for excitation and are inactive in the immobile joint or when the joint is moving at constant speed, but are responsible for signaling acceleration and deceleration

of the joint. Thus, Pacinian corpuscles are considered solely as dynamic mechanoreceptors.²³

Due to the information provided by these mechanoreceptors in the ACL, the central nervous system can appreciate speed, acceleration, direction of movement, and the position of the knee joint.^{4, 5}

Free nerve-endings (Figure 2.2) constitute a pain-receptor system for the tissues of the knee joint. An individual's apparent insensitivity to immediate pain after an ACL injury may be explained by the small concentration of free nerve-endings found in the ligament.⁵

Figure 2.2¹⁷
Mechanoreceptors in the Anterior Cruciate Ligament

Function of the ACL

Mechanical Role

According to Ellison and Berg⁷, to understand the function of the ACL, an understanding of knee joint kinematics is essential. Arthrokinematics refers to the study of movement at a joint that accompanies physiological range of motion.²⁴ Osteokinematics refers to the study of the movement of a bone in space without regards to the effects at the joint.²⁴ Since the knee is a modified ovoid joint, there are two degrees of freedom of movement. The ranges of motion that occur at the knee joint are flexion, extension, internal rotation, and external rotation. Flexion and extension occur about a transverse axis in the sagittal plane while internal and external rotation occurs about a vertical axis in the transverse plane.⁷

In the sagittal plane, flexion and extension of the knee occur by a combination of rolling and sliding motions. The arthrokinematics in the sagittal plane is due to the shape of the femoral condyles.⁷ Anteriorly, the femoral condyles are flatter and oval-like in geometry. Posteriorly, the condyles are more curved or spherical. Due to the geometry of the femoral condyles, rolling predominates in the early degrees of flexion while sliding prevails in the latter degrees of flexion.⁷

In the horizontal plane, internal rotation and external rotation occur as a result of spinning about a vertical axis. Of special interest is the screw home mechanism, which entails external rotation of the tibia relative to the femur with terminal knee extension.⁷ The screw home mechanism gives the knee maximum joint stability in preparation for body weight loading in the single-leg stance phase of the gait cycle.⁷ This mechanism is a result of the inequality of bony geometry observed in the sagittal plane. Due to the smaller surface area of both the lateral tibial plateau and lateral femoral condyle, the lateral side of the knee joint achieves congruency at 30° of flexion.⁸ A continuation of simple extension is therefore impossible, however internal rotation of the femur about a vertical axis is possible. As this occurs, full congruence of the lateral condyle is delayed and continuing extension is possible. Therefore, internal rotation of the femur (on the tibia) must occur at 30° of flexion to achieve full knee extension.

With an understanding of knee joint kinematics, the function of the ACL as a passive restraint can be better appreciated. The major function of the ACL is to prevent excessive anterior tibial translation in various degrees of flexion.^{12, 25} According to Butler et al.²⁵, the ACL provides 85% of the restraining force to anterior tibial displacement at 30° and 90° of knee flexion. In flexion, the anteromedial band of the ligament is the most important in preventing anterior tibial translation, whereas the posterolateral band contributes mostly to stability in extension.^{7, 12} The ACL also prevents hyperextension of the knee, limits excessive tibial rotation (internal rotation more so than external rotation), and is a secondary restraint to both valgus and varus stresses.^{7, 12, 26} Finally, the ACL enhances the screw home mechanism as the knee approaches terminal extension.⁷ Stability of the knee in terminal extension is of maximal importance, especially to athletes who participate in activities involving vigorous cutting, jumping and rapid deceleration.

If the ACL is ruptured or plastically elongated, the synchronous rolling and gliding of the knee joint becomes abnormal and the knee becomes vulnerable to degenerative changes secondary to unguided femoral motion.^{7, 27} A significant injury to the ACL often results in anterolateral instability of the knee, especially if the lateral collateral ligament and the posterolateral complex of the capsule are also damaged.^{3, 28} Thus, decreased stability of the knee associated with functional disability is a common feature of the ACL deficient knee.²⁹

According to Torzill et al.³⁰, there are four factors that affect joint stability:

1. Passive soft tissue structures.
2. Active muscle force.
3. Externally applied forces and moments, as occur during normal physiologic functions such as gait and stair climbing.
4. Geometry of the articulating surfaces.

Traditionally, the mechanical role of the ACL as a passive restraint against excessive joint displacements has been emphasized. The integrity of the ACL plays an important role in determining the passive joint stability of the knee. Passive joint stability

is determined by the joint geometry and the mechanical properties of the tissues within and around the joint. According to Noyes et al.³¹, a complete failure of the human ACL occurs at stress levels of about 1725N, while bone avulsions and ligamentous microfailures occur at lower stress levels. However, it has been demonstrated in vitro that during strenuous activities such as downhill skiing, the load on the knee joint and its ligaments may substantially exceed potential injury levels.³² Consequently, the knee joint must rely on mechanisms other than the mechanical properties of its ligaments to maintain functional joint stability during strenuous physical activities and to prevent injuries to the ligaments.

Functional joint stability can be defined as the condition in which the joint is stable and does not give symptoms during physical activities. The lack of a strict relationship between the passive stability and the functional stability of the knee joint has been established in several studies.^{33, 34}

Functional joint stability is determined by the interaction of a number of factors, including the passive restraints of the joint, the joint geometry, the friction between the cartilage surfaces, and the load on the joint caused by compression forces resulting from body weight and the muscles acting on the joint.²¹ According to Johansson et al.²¹, the load imposed on the joint is one of the most important determining factors of functional joint stability.

Using cadaver knees, Markolf et al.³⁵ demonstrated that by increasing the load on the knee joint greatly enhances the anterior-posterior, medial-lateral, varus-valgus, and torsional stiffness. This implies that when the load on the knee joint is increased, the application of a given external force will result in less tibial displacement, and thus, functional joint stability is increased. Markolf et al.³⁵ concluded that joint load, whether generated by gravitation, dynamic, or muscular forces, is an important protective mechanism that avoids ligament strain.

Similar results were produced in a study conducted by Torzill et al.³⁰ Using nine intact cadaveric knees and four ACL deficient knees, anteroposterior translation was measured at 0°, 15°, 30°, 45°, and 90° of knee flexion after the application of an

anteroposterior force of 100 N, a joint compressive load of 0 N, 111 N, 222 N, 333 N, or 444N, and a quadriceps force of 0 or 133 N. The investigators found a significant decrease in total anteroposterior translation after the application of a joint-compressive load, a quadriceps force, or a combination of both. This occurred for all combinations of joint-compressive load and quadriceps force, at all flexion angles tested, and in both the intact and the ACL deficient knees. Thus, the activity of the muscles surrounding the knee joint can have a direct impact on functional joint stability.

Thus, although a precise diagram of the neurocircuitry of dynamic knee joint control is not agreed on by investigators, there is clear evidence that the neuromuscular system is capable of altering the strains imposed on the passive restraints of the knee and contributes to functional joint stability during physical activities.³⁶⁻⁴⁰

Numerous studies have demonstrated that while a hamstring contraction reduces ACL strain, a quadriceps contraction increases ACL strain.^{38, 41-45}

Renstrom et al.³⁸ observed that hamstring activity decreased ACL strain relative to the passive normal strain at angles greater than 60° whereas isometric quadriceps activity significantly increased the strain within the ACL at angles of 0° to 45°. A *in vivo* study conducted by Beynnon et al.⁴⁴ measured the strain in the intact ACL during active range of motion (ROM) of the knee, with or without an ankle weight, and during isolated isometric quadriceps and hamstring contractions. Strain values were also measured during simultaneous contractions of the quadriceps and the hamstrings. Active ROM was found to produce an ACL strain response that depended on the angle of knee flexion and the level of quadriceps activity. In the study, the ACL strain values were at a minimum with 90° of knee flexion and were at a maximum with terminal knee extension during active ROM. With the addition of an ankle weight, the increase in the activity of the quadriceps resulted in a greater ACL strain value. Isometric quadriceps contractions at 15° and 30° of knee flexion were shown to increase the ACL strain whereas there were no changes in the ACL strain value relative to the relaxed state at 60° and 90° of flexion. Isometric hamstrings contractions did not produce a change in ligament strain at any flexion angle. Simultaneous contraction of the quadriceps and the hamstrings produced an increase in strain value only at 15° of flexion. Therefore, resisted knee extension

exercises between 0° and less than 60° of knee flexion with the tibiofemoral joint unloaded (open kinetic chain) should be avoided in the early stages of rehabilitation after ACL reconstructions.⁴⁴

According to Borsa et al.⁴⁶, the functional instability that occurs after an injury to the ACL is due to the combined effects of excessive tibial translation and a lack of reflex stabilization of the muscles surrounding the knee joint. The lack of reflex stabilization of the knee is thought to be secondary to a diminished sensory feedback mechanism. Thus, the ACL is thought to have a sensory role as well as its well-known mechanical role in the knee joint.

Sensory Role

Since the discovery of mechanoreceptors in the ACL, it has been suggested that sensory information from the ligament assists in providing dynamic stability to the knee joint by contributing to proprioception and kinesthesia, and thus, to muscular coordination and reflexes.^{4, 5, 18, 29} The role proprioception plays in the prevention and progression of injury is currently receiving a great deal of attention in the literature.^{47, 48} The results of numerous studies support the existence of a sensory role for the ACL.^{40, 49-51}

Somatosensory evoked potentials (SEPs) were recorded by Pitman et al.⁵¹ at the cerebral cortex upon electrical stimulation of the ACL. SEPs measure the electric potentials evoked in the cerebral cortex upon stimulation of a peripheral neuroreceptor. The results of the study provide direct evidence for the presence of a proprioceptive function of the ACL. Krauspe et al.⁵⁰ demonstrated the afferent fibers of the ACL were activated by local mechanical stimulation of the ACL and by movements of the knee joint. In this study, passive motion alone was suffice to elicit impulse generation, but at full extension and combined with rotation, a higher degree of stimulation was generated. Finally, by using a dynamic histological technique, Madey et al.⁵² established a pathway between the spinal dorsal ganglion and the posterior capsule of the knee and the ACL.

The Neurophysiology of Proprioception and Kinesthesia

Both proprioception and kinesthesia, first introduced by Sherrington⁵³ and Bastian⁵⁴, respectively, are specialized types of the sense of touch. Both are involved in the control of movement and posture. Proprioception and kinesthesia arise from discharge of sensory receptors in the skin, musculotendinous units, ligaments, and joint capsules, from centrally generated motor commands, and from interactions between these afferent and efferent signals.^{6, 55} These sensory receptors transduce mechanical deformation to a neural signal that modulates conscious and unconscious responses. Visual and vestibular centers also contribute afferent information to the central nervous system (CNS) regarding body position and balance.⁴⁷ Proprioception and kinesthesia are hypothesized to contribute to the motor programming for neuromuscular control required for precision movements and muscle coordination.^{6, 47} Thus, proprioception and kinesthesia play a role in functional joint stability.

According to Gandevia⁵⁵, the two terms, proprioception and kinesthesia, have become almost synonymous and are used to cover almost anything concerned with the control of movement. However, proprioception and kinesthesia are two distinct terms. Proprioception refers to the unconscious sensation contributing to movement control, or reflex control of movement without the need of conscious awareness.⁵³ Kinesthesia involves conscious awareness; these include sensations of limb movement and position, sensations of force and heaviness, and sensations of the timing of muscular contractions.⁵⁴ Collectively, kinesthesia and proprioception encompass a group of sensations.⁵⁵ First is the traditional sensation of position and movement of the limbs and trunk. Second, there are sensations related to muscle force, including effort, tension, heaviness and stiffness. Third, sensations exist for timing of muscle contractions. Fourth, there is a sensation of body posture and size as part of a "schema" encompassing more than one joint.

Other definitions of proprioception and kinesthesia, often more simplistic, can be found in the literature. For example, Barrack et al.⁵⁶ refers to proprioception as the conscious awareness of the limb position in space and kinesthesia as the awareness of

joint motion. Beard et al.²⁹ divided proprioception into three components: (1) static awareness of joint position, (2) kinaesthetic awareness, and (3) closed-loop efferent activity that is required for the reflex response and the regulation of muscle stiffness.

For the purpose of this thesis, unless otherwise specified, the term proprioception will be used to encompass both the conscious and unconscious sensation of joint movement and joint position.

The sense of proprioception is made possible by mechanoreceptors that transduce modulated neural signals which are transmitted via cortical and reflex pathways through different nerve fiber types that are specific for each modality.²² An increased stimulus of deformation is coded by an increased afferent discharge rate or an increased population of activated receptors.⁵⁷ The sense of proprioception is proposed to be carried along by large-diameter myelinated nerve fibers that have high conduction velocities, while the sensations of pain are conducted by smaller diameter nerve fibers that have slower conduction velocities.^{22, 57}

Sensory information from receptors in the joint capsules, ligaments, skin and musculotendinous units are transmitted via articular nerves through the posterior roots to the spinal cord and ascend through the posterior column (dorsal-column-lemniscal) where they are then conducted to the post-central gyrus of the cerebral cortex.²² It has been noted there is a disproportionately high cortical representation for the lower limb, which has been taken as evidence of the importance of proprioceptive input from the lower extremity.²²

Conventionally, the sensory units in the limbs that are responsible for proprioception and kinesthesia are divided into three categories: skin, joint, and muscle.⁵⁷ Each of these categories of afferents is considered to be independent and act in parallel with the others. However, it should be noted that within the area of a joint, tendons and periarticular connective tissue and capsule may not be separable as to function when loads are transmitted across them. Thus, proprioception and kinesthesia appear to rely on simultaneous activity in a number of types of afferent endings.

However, in the literature, there is the continual debate as to which group of receptors are the main source of proprioception, and specifically, of kinesthesia.

Skin Mechanoreceptors

It is generally agreed upon that muscle receptors are the main contributors to kinesthesia and proprioception in the literature. There is much debate among investigators on whether joint and skin receptors have only a facilitatory function or actually contribute to proprioception and kinesthesia. Edin and Abbs⁵⁸ has demonstrated that a majority of the low threshold cutaneous mechanoreceptors located on the back of the human hand respond to movements at one or more nearby joints. Cohen et al.⁵⁹ demonstrated that active arm movement evoked complex patterns of tactile activity in the anterior somatosensory cortex of awake, behaving, primates. These results has added impetus to the argument that skin receptors may play an important role in kinesthesia and motor control.

Clark et al.⁶⁰ tested position sense in the human knee joint, with anesthesia of skin, joint, or skin and joint together. The investigators blocked cutaneous afferents by anesthetizing a 15 centimeter band of skin around the knee and blocked joint afferents by injecting a local anesthetic into the joint space. Clark et al.⁶⁰ concluded that joint awareness does not depend on sensory input from either receptors in the joint or the skin around the joint. The insignificant results may be secondary to the lack of total sensory loss produced. The problem in eliminating just cutaneous afferents is that in most joint, it is difficult to anesthetize the skin alone.

Edin and Johansson⁶¹ conducted a study examining the relative importance of cutaneous inputs in kinesthesia. The study produced an unexpected finding that skin afferent inputs may have precedence over muscle spindle inputs with regard to kinesthetic and proprioceptive processing as expressed by perception and motor responses. Edin and Johansson⁶¹ proposed that the relative importance of cutaneous input to kinesthesia and proprioception have been underestimated for the following reasons:

1. "The exquisite sensitivity of skin afferents to skin deformation has only been recently quantified and has not previously been taken into account."(p.247)

2. "The possibility that skin afferents may provide information about joint configuration by means of encoding patterns of skin deformation rather than as simple "joint angle transducers" has not been considered."(p.247)
3. "Distant mechanical effects of stretching muscles have not been taken into proper account when interpreting experimental data related in particular to the involvement of muscle spindle inputs in signaling imposed joint movements."(p.247)

Thus, Edin and Johansson⁶¹ concluded that although skin mechanoreceptors are not the only source of information about joint position, the importance of these receptors has been underestimated in the past and that, under some circumstances, the information provided by these afferents has precedence over all other sources of proprioceptive information.

Muscle Mechanoreceptors

Muscle spindles are distributed throughout the belly of the muscle and send information to the nervous system about either the muscle length or rate of change of its length. Muscle spindles have a sensory and motor innervation.⁵⁵ The sensory component consists of one primary and several secondary spindle receptors. The primary spindle endings innervate both the nuclear bag fibers and the nuclear chain fibers. The secondary spindle endings usually innervate only the nuclear chain fibers. Primary spindle endings give rise to group Ia afferents and secondary endings to slower conduction group II afferents. Primary spindle afferents are much more sensitive to dynamic stimuli such as stretch or tendon taps than secondary afferents. The high sensitivity of primary spindle endings means that their exact intramuscular location modifies their response, as all regions of a muscle do not lengthen uniformly.⁵⁵

The motor innervation consists of fusimotor axons, or gamma-motoneurons, which innervate several spindles; and the less frequent skeletofusimotor axons, or beta-motoneurons, which innervate intrafusal and extrafusal muscle fibers.⁵⁵ Fusimotor axons are distinguished by their innervation of particular types of intrafusal muscle fibers and their action on primary and secondary afferents. There are two types of fusimotor axons, dynamic and static. Dynamic fusimotor axons innervate bag₁ (dynamic) fibers while static fusimotor axons innervate bag₂ (static) fibers and nuclear chain fibers

Golgi tendon organs are uniquely placed to record muscle unit forces.⁵⁵ Over 90% of a tendon organ is located at the muscle junctions, with the remainder in the tendon. This encapsulated receptor is "in series" with a few muscle fibers and "in parallel" with others inserting around it. The number of muscle fibers inserting into a tendon organ ranges from 5 to 50, with 10 to 20 being common in humans.⁵⁵ The adequate stimulus for tendon organs seems to be contractile forces acting at the receptor rather than passive stretch. They have a lower threshold for active force than for that produced by passive stretch. Tendon organs are innervated by Ib afferents. These Ib afferents have conduction velocities that overlap those of primary muscle spindle afferents but with a fractionally lower mean value.⁵⁵

Since the response of muscle spindle afferents is known to be a function of muscle length, muscle afferents are able to provide an unconfounded, unidirectional signal of joint movement.⁵⁷ Around 1960, due the results of various experiments, spindle discharges were thought to lack any access to conscious sensation, or kinesthetic awareness.⁵⁵ Instead, information from muscle spindles were seen as reserved for the unconscious control of movement, or proprioception. However, after a study conducted by Goodwin et al.⁶² in 1972, the pendulum swung, and currently, muscle afferents are generally believed to be the principal source of kinesthetic and proprioceptive signals.

In the study conducted by Goodwin et al.⁶² in 1972, it was demonstrated that when vibration of 100 hertz was applied to the tendon of the biceps or the triceps muscle, an illusion of elbow motion was created. Subjects in the study consistently thought the elbow was in position that it would have assumed if the vibrated muscle had been stretched. Thus, excitation of muscle afferents, by vibration of the muscle, caused sensations of joint movement and position.

In another study conducted by Goodwin et al.⁶³, where the joint and cutaneous afferents of the index finger or the whole hand were inactivated by anaesthesia, kinesthetic sensations were still evoked by passive joint movements. It was also noted in the study that when subjects tensed their muscles acting around the index finger, their kinesthetic awareness was enhanced.

Grigg et al.⁶⁴ studied the individual's ability to detect passive joint movement and duplicate positions of the hip shortly after total hip replacement. The results indicated the ability to detect joint position was retained after total hip replacement. This lead the authors to conclude that joint position sense is not totally dependent on the joint capsule or the surfaces of the hip joint, and that extracapsular components (i.e. muscle receptors) exist.

In summary, there is strong evidence that muscle afferents play an important role in proprioception and kinesthesia. However, this role is probably not a simple one. For example, in the study conducted by Goodwin et al.⁶³ where kinesthesia persists after paralyzing joint afferents but preserving muscle afferents, the resulting kinesthesia was deteriorated from the normal. Moberg⁶⁵ also demonstrated that when the hand was anesthetized and finger muscle afferents were unanesthetized, kinesthetic acuity in the fingers was much lower than normal. Thus, it appears that in order to have normal proprioceptive sensations and normal acuity, it is necessary to have sensory systems other than those in muscles functioning simultaneously. In addition, in studies utilizing longitudinal vibration of a muscle tendon is probably no a selective activator of muscle spindle afferents. Activation of muscle spindle afferents by vibration may also increase muscle tone, which may ultimately affect joint afferents owing to the mechanical coupling between some muscles and joint capsules.

Joint Mechanoreceptors

Joint motion will stretch the joint capsule on one side of the joint and may also compress it against the underlying bone.⁵⁷ Structures on the other side of the joint will be unloaded by the rotation. Ligaments may also be loaded in rotational movements of the joint. Therefore, it is possible that mechanoreceptors originating in these tissues may have a role in proprioception and kinesthesia.

It is still a popular belief that the contribution of joint afferents to proprioception is important only at limits of joint motion.^{18, 21, 23} This belief originated from most of the early investigations that found a majority of joint afferents to signal near full flexion and extension, while few units have their active range in the mid-position (i.e. midrange

units).^{18, 21, 23, 55} Thus, it was concluded that true joint receptors do not contribute to proprioception and kinesthesia since they could not inform the CNS about joint angle throughout the full range of movement. This popular hypothesis would explain the results of the study conducted by Grigg et al.⁶⁴ where the hip joint capsule was surgically removed and deficits in kinesthesia were not observed when the joint was moved through intermediate positions.

However, in study conducted by Ferrell⁶⁶ in 1980 using feline knees, a higher proportion of midrange was observed than previously in the posterior articular nerve of the knee, located in the capsule as well as in the knee joint ligaments. Ferrell⁶⁶ also observed a higher frequency of ligamentous afferents among the midrange units than among the end range units in the knee joint capsule. Midrange units or afferents probably arise from Ruffini endings.²¹ Thus, it appears that joint receptors may contribute to proprioception and kinesthetic awareness throughout the full range of joint motion.

In a study to assess the role of joint receptors in human kinesthesia when intramuscular receptors can not contribute, Ferrell et al.⁶⁷ concluded that the discharge of joint receptors can produce perceived signals of joint motion and that under normal conditions these receptors may duplicate the kinesthetic input from muscle spindle afferents. Kinesthetic acuity was tested at the distal interphalangeal joint of the middle finger when the hand was positioned so that the joint was effectively disengaged from its muscular attachments.

Despite the new found evidence for joint mechanoreceptors contributing to proprioception and kinesthesia, the popular belief is still that muscle afferents play the predominate role in proprioception and kinesthesia. According to Grigg et al.⁵⁷, the following reasons support the lack of major proprioceptive roles for joint afferents, especially those originating from ligamentous structures such as the ACL:

1. "There is a scarcity of nerve endings. While there are relatively large numbers of afferent neurons having endings in the joint capsule, there appear to be not more than a few ligament afferents that originate in the ACL."(p.12)

2. "Ligament afferents would function as nonspecific limit sensors. ACL afferents are not active when the knee is in a neutral position. They have been shown to respond to stimuli that would cause tensile loading of the ACL: rotations into the limit of flexion, extension, and internal or external rotation. Since ligament tension can be caused by a number of different types of rotations, the mechanoreceptors in them are poor candidates to subserve proprioceptive sensations of movements in specific directions. While neurons innervating the collateral ligaments are less well documented, they also appear to be tension sensitive, and thus to be subject to the same reservations as those stated for ACL afferents."(p.12)

However, with the discovery of midrange afferents within the knee joint capsule and ligaments, the debate regarding the significance of joint afferents in proprioception and kinesthesia continues. In addition, the small number of midrange units found in joints does not necessarily mean that the midrange units have less influence on proprioception and kinesthesia. The strength of such an influence can not be assumed to be directly proportional to the number of units engaged.²¹

Many studies have demonstrated that both proprioception and kinesthesia awareness of the knee are altered after an injury to the ACL.^{29, 40, 68-72} According to Lephart et al.⁴⁷, kinesthesia awareness is essential for proper joint function in sports, activities of daily living, and occupation tasks, whereas proprioception is essential in modulating muscle function and initiating reflex stabilization of joints.

The Role of Proprioception in the Function of the Knee Joint

Diminished proprioception in joints are secondary to injury. Decreases in proprioception may lead to further instability secondary to poor coordination of the dynamic stabilizers.⁴ This ultimately may initiate a vicious cycle of reinjury secondary to proprioceptive deficiency.^{21, 47} Since proprioception is thought to be involved in mediating the control of muscular coordination and reflexes, it is the postulation that these mechanisms of the knee depend, to a certain degree, on the proprioceptive contribution of the ACL.^{4, 29, 68} Kennedy⁴ proposed that a decrease in the proprioception of the knee, secondary to an injury of the ACL, may contribute to progressive knee instability (Figure 2.3). After studying professional ballet dancers for knee joint laxity, Barrack et al.⁵⁶ concluded that decreased joint position sense (reproduction of passive positioning) may indicate below normal protective reflexes, which may increase the chances of acute or chronic injuries and degenerative changes to occur.

Figure 2.3⁴

Hypothesized Neurogenic Contribution to Progressive Knee Instability

Protective Mechanisms

Traditionally, joint afferents have been regarded as “limit detectors”, responsible for triggering protective reflexes when the joint is threatened by hyperextension, hyperflexion, or excessive rotation.²¹ However, this traditional view contains considerable conceptual problems, since ligamento-muscular protective reflexes do not

seem to be able to act in time to protect the ligaments from injury unless the threatening event is very slow.^{73, 74} In a study conducted by Yasuda et al.⁷⁴, it was demonstrated that following a lateral impact, elongation of the MCL and ACL reached peak values by 70 ms. This finding lead to the conclusion that contraction of the leg musculature would not protect the MCL and ACL from injury when a lateral impact load is applied to the knee.

The results of the study conducted by Yasuda et al.⁷⁴ are in agreement with the results obtained by Pope et al.⁷³ In their study, Pope et al.⁷³ reported that 34 ms would elapse between the loading of the MCL and ligament rupture, while 89 ms would pass between ligament loading and the initiation of a ligamento-muscular protective reflex. The calculation of the latter latency seems to be accurate, as it agrees well with the findings of Petersen and Stener⁷⁵, who showed that a tap at the site of a partial rupture of the MCL activated the sartorius muscle with a latency to the EMG of 76 ms.

According to Johansson et al.²¹, this "time argument" has been widely used to place the mechanical properties of the knee joint ligaments among the most important factors subserving joint stability. However, this view disregards the crucial point in the discussion about the importance of muscles in the control of knee joint stability: the state of the changeable muscle stiffness at the time of the displacement, which will to a considerable degree determine the load on the joint and thereby the actual stability of the joint at the time of the trauma.²¹

Stiffness is defined as the ratio of force change to length change.²³ Stiffness of a muscle can be described as two components:

1. Intrinsic muscle stiffness.
2. Reflex-mediated muscle stiffness.

According to Johansson et al.²¹, the intrinsic muscle stiffness is determined by the viscoelastic properties of the muscle and the existing acto-myosin bonds. Intrinsic muscle stiffness depends greatly on the existing acto-myosin bonds or the degree of muscle contraction in a given moment. Therefore, intrinsic muscle stiffness is partly the result of the preceding reflex-mediated muscle stiffness. Reflex-mediated muscle

stiffness is determined by the excitability in the gamma-motoneuron pool, descending commands, autogenic and heterogenic reflexes. The variability in the overall muscle stiffness during dynamic condition is largely due to modulation of the reflex-mediated component.

Thus, when the knee is subjected to force threatening to displace it, there are two possible ways in which the muscles can protect the knee from displacement^{37, 49, 76-78}:

1. By a preparatory (preset) increase in the muscle stiffness, which will increase the load on the knee and thereby enhance the functional stability of the joint.
2. By a direct reflex counteraction of the applied force or the resulting displacement.

Sensory information from ligamentous afferents are hypothesized to contribute to both mechanisms. However, since simple protective reflexes have been shown to be too slow to protect the joints and associated ligaments during fast perturbations, the main contribution of ligamentous afferents to functional joint stability may be a continuous preparatory adjustment of intrinsic muscle stiffness through the reflex-mediated component.²¹

Maintenance of Joint Integrity

In a study conducted by Barrett et al.⁷⁹, the investigators examined the question, "To what extent, therefore, does lack of good proprioception predispose to the development of degenerated change?"(p.53) Three groups were involved in this study:

Group I - Humans with normal knees.

Group II - Humans with osteoarthritic knees.

Group III - Humans with replaced knees.

Results demonstrated that static awareness of joint position deteriorated with age and was further impaired at all ages in osteoarthritic knees. Individuals with total knee replacements exhibited greater accuracy than did those with osteoarthritic knees. Barrett et al.⁷⁹ concluded that though loss of static joint position sense may be a consequence of the process of osteoarthritis, it may equally be a primary factor in the initiation of joint deterioration.

In a study using dogs, O'Connor et al.⁸⁰ examined the effects of denervation of the knee joint. Four experimental groups were used:

Group A - Articular neurectomy was carried out.

Group B - The ACL was cut, but the knee was left normally innervated.

Group C - The ACL was cut, and the knee was also denervated.

Group D - Control group.

Several criteria were used to judge the effect of joint denervation. O'Connor et al.⁸⁰ observed the locomotion of the dogs and they sacrificed the animals and looked for histological evidence of osteoarthritis. The results of the study were:

Group A - The dogs demonstrated no signs of locomotor problems and they did not develop arthritis.

Group B - The dogs limped until they were sacrificed. They developed arthritis.

Group C - The dogs limped until they were sacrificed. They developed the most severe arthritis. Three of the 15 dogs in this group developed subchondral fractures.

According to O'Connor et al.⁸⁰, the results show that an animal uses proprioceptive information from joint afferents in maintaining the integrity of the joint. Through proprioceptive feedback, the animal with the unstable joint can learn to adopt movement strategies that minimize tissue stress and potentially damaging stimuli. The results of the study suggest that when proprioceptive feedback is absent, damage to the joint occurs.

Muscular Co-Contraction

Numerous studies have indicated the hamstrings as essential antagonists in maintaining joint stability in the extension motion.^{37, 81-83} Draganich et al.⁸² demonstrated that there is co-activation of the hamstrings with the quadriceps during monoarticular quasi-static knee extension. The EMG signals of all of the knee flexors and extensors increased with increasing loads on the ankle, and also increased as the knee extended. This observation supports the hypothesis that the activity of the hamstrings, combined with the restraint of the ACL, acts to prevent excessive anterior displacement of the tibia during functional activities.

Baratta et al.⁸¹ concluded that co-activation of the hamstrings during maximal effort, slow isokinetic contractions of the quadriceps is necessary to aid the ACL in

maintaining joint stability, equalizing the articular surface pressure distribution, and regulating the joint's mechanical impedance. Furthermore, a reduced co-activation pattern of the antagonist may increase the risk of ACL damage.⁸¹ The study included three groups of subjects:

Group 1 - Nonathletic and healthy subjects, none of whom were active in any sports or exercise program.

Group 2 - High performance athletes. None of the subjects in this group had performed any hamstring exercises prior to the test.

Group 3 - High performance athletes. All subjects in this category routinely exercised their hamstring muscles (i.e. hamstring curls).

Baratta et al.⁸¹ observed that high performance athletes in Group 2 with hypertrophied quadriceps demonstrated strong inhibitory effects on the hamstring coactivation patterns when compared to Group 1, while those in Group 3 had a coactivation pattern similar to Group 1.

Hagood et al.⁸³ observed that an increase in limb velocity into knee extension resulted in an increase in the contribution of the hamstrings, especially during terminal extension. The authors explained this increase in hamstring activity as a way to provide the limb with "dynamic braking such that it does not exceed its physiological range of motion limits."⁸³ Since ACL strain significantly increases in the terminal range of knee extension, it appears the hamstrings may have an ACL-emulating role.³⁷ Finally, the literature has shown that specific training can improve the contributions of the hamstrings to knee joint stiffness as well as reducing laxity, thereby reducing the risk of ligamentous damage.^{70, 81}

The literature suggests that the mechanoreceptor system of the ACL may be one of the mechanisms responsible for reflex co-activation of the hamstrings with the quadriceps.^{4, 5, 15, 18} If the ACL is solely responsible for providing the sensory information required for the co-activation of the hamstrings, this muscular activity would be absent in ACL deficient knees. In a study conducted by Solomonow et al.³⁷, hamstring activity pattern was monitored during loaded knee extension (quasi-isometric

conditions) in two groups: ACL deficient and ACL intact. Activity pattern of the hamstrings was also monitored during mechanical loading of a cat's ACL. It was hypothesized that the ACL might be involved in providing "reflex sensory information regarding ligament loading or deformation that may request the muscles to assist in maintaining joint stability as conditions arise when the ligaments are overloaded."³⁷ Solomonow et al.³⁷ demonstrated that mechanical loading of a cat's ACL resulted in an increase in the electromyograph (EMG) activity of the hamstrings. This increase in the EMG activity of the hamstrings was evident only with the application of a high mechanical load (130N). Similar responses were elicited in both the ACL intact and ACL deficient knees during loaded knee extension, indicating the existence of an alternative reflex arc, unrelated to the ACL receptors, that was available to maintain joint integrity. Solomonow et al.³⁷ proposed that a direct reflex arc exists from the ACL to the hamstrings with the purpose to maintain functional joint stability. In addition, a secondary reflex arc exists from the receptors in the muscles or joint capsule, providing activation of the hamstrings upon knee instability. This secondary reflex arc has a longer response time than the direct reflex arc, as well as having a simultaneous inhibitory input to the quadriceps, and it can provide sufficient joint stability if the hamstrings are exercised and are well conditioned.³⁷ Solomonow et al.³⁷ concluded that the hamstrings are a load regulator of the knee during extension, increasing their activity when the ACL is overloaded or when the "geometric configuration disallows the ligament to perform satisfactorily in maintaining stability."(p.211)³⁷ It is doubtful, however, that either the direct ACL-hamstring reflex arc or the secondary reflex arc can protect the intact or reconstructed ACL if high loads are applied rapidly.^{6, 78} Under rapid loading conditions, the ligament may be loaded and ruptured before sufficient muscle tension to protect the ligament can be generated.

Contrary to the findings of Solomonow et al.³⁷, in a study using chloral-anesthetized cats, Pope et al.³⁶ failed to produce any reflex hamstring activity with mechanical loading of the ACL (up to 125 N). According to Pitman et al.⁵¹, it is difficult to develop a model in the cat, and especially in the human, for accurate and significant

mechanical stimulation. Mechanical loads are complex and may be affected by anesthesia or by the duration or type of load. Therefore, as summarized by Solomonow et al.⁷⁸, the sources of antagonist activity are probably the motor cortex, the velocity-sensitive component of the muscle spindle afferents, as well as other receptors in the joint capsule and ligaments.

Grabiner et al.⁸⁴ conducted a study to assess whether an automatic hamstrings excitation could be elicited during maximum effort isometric knee extension performed in minimum elapsed time. Results failed to support the contention of an automatic ACL-hamstrings synergy as proposed by Solomonow et al.³⁷. However, contrary to other studies found in the literature, Grabiner et al.⁸⁴ conducted the study using static knee extension conditions while others have used isokinetic and quasi-dynamic conditions.

The Role of the ACL in Neuromuscular Control: Possible Mechanisms

In 1944, Ivar Palmar⁸⁵ speculated that the ligaments supply the CNS input that makes neuromuscular control of the knee joint possible. The exact mechanism by which muscular reflexes and the continuous regulation of muscle stiffness are initiated is a subject of some debate. It is uncertain whether some impulses generated from the mechanoreceptors result directly in stimulation of alpha motor neurons or whether the effect is primarily on the gamma efferent muscle spindle system. It should be noted that the current interest in the neuroreceptor function of the ACL is really a resurgence of interest in a function that has been suggested in the past.

The number of studies on skeletomotor effects caused by natural stimulation of sensory endings in the knee joint is limited. Few studies using EMG have indicated that the activity in the hamstring muscle might be altered by increased tension in the ACL.^{37, 81} Yet several studies have indicated that ligament stretches with moderate loads (i.e. less than 130 Newtons) do not exert much influence directly on the skeletomotor system.^{36, 84}

Freeman and Wyke⁸⁶ in 1967 theorized that Type I and II joint mechanoreceptors project directly onto the muscle spindle system and influence the gamma-motor neurons, which ultimately has an effect on the primary muscle spindle afferents. These investigators concluded that reflexes from articular mechanoreceptors take part in the normal reflex coordination of the muscle tone in posture and movement. Thus, the mechanoreceptors of the ACL, through the gamma efferent muscle spindle system, may participate in the regulation and pre-programming of the muscular stiffness around the knee joint and thereby of the knee joint stiffness.^{18, 49} Currently, Johansson and coworkers^{18, 21, 23} are strong proponents of this theory. After conducting several thorough investigations, Johansson and coworkers^{18, 21, 23} concluded that modest stretching of the cruciate and collateral ligaments (5 to 40 Newtons) elicits activity in the low-threshold mechanoreceptors.^{49, 76, 77} Activity in these ligamentous afferents was found to primarily influence the gamma efferent muscle spindle system, rather than causing direct reflex effects on the alpha motoneurons. Johansson and coworkers^{18, 21,}

²³ found the effects of the ligamentous receptors on the gamma efferent muscle spindle system to be potent and frequent and may induce major changes in responses of the primary muscle spindle afferents. As the activity in the primary muscle spindle afferents modifies stiffness in the muscle through the reflex-mediated component, the ACL mechanoreceptors may, through the gamma efferent muscle spindle system, participate in the coordination and continuous preparatory adjustment of muscular stiffness around the knee joint during dynamic conditions. Specifically, Sojka et al.⁷⁷ demonstrated that stretching of the posterior cruciate ligament of the ipsilateral knee causes changes in dynamic and/or static sensitivity of the primary muscle spindle afferents to sinusoidal stretching. The changes in the sensitivity of the primary muscle spindles were concluded to be due to reflex actions of stretch/tension-sensitive receptors in the cruciate ligaments onto fusimotor neurons. Similar results were found with stretching of the ACL and the collateral ligaments.^{49, 76} As proposed by Solomonow et al.³⁷, Johansson et al.¹⁸ also concluded there was the possibility of the ACL directly influencing the alpha motor neuron neural pathway, but only at high mechanical loading.

Surgical Considerations Relating to Proprioception

The significance of proprioception is apparent with expanded research into its role in normal joint function, specifically in dynamic stabilization.^{4, 21, 48} Initial work in proprioception focused on the documentation of diminished proprioception in injured joints. Since then, the role of proprioception in the initiation and propagation of injury and in the rehabilitation that follows has been further elucidated. From this, its role in surgery is gradually being defined.⁸⁷

Preservation of Afferents

According to Safran et al.⁸⁷, the role of surgery in proprioception, and the current role of proprioception in surgery, is unclear due to the lack of scientific research and clinical studies. It is undetermined to what degree are the biomechanics of the knee joint and the vulnerability of its ligaments depend on the innervation of the repaired or reconstructed ACL. Data provided by several investigators, especially Johansson et al.⁴⁹, suggest that the innervation of the ACL is important for the stability of the joint and for the integrity of the ligament. Thus, the loss of innervation of the ACL may be responsible for the altered biomechanics of the knee and the vulnerability of its ligaments after injury or operative treatment. According to Safran et al.⁸⁷, operations around the knee joint should be done in such a way that the integrity of its mechanoreceptors and afferent nerves of its surrounding structures, such as the capsule, the collateral ligaments, the fat pad, the synovium, and the perimeniscal tissue, are preserved. The primary goal during surgery would be to save as much sensory function as possible. The recent trend towards arthroscopic surgery of the knee, ankle, and shoulder may have benefits in the reduced compromise of proprioception postoperatively as compared to standard open procedures.⁸⁷ With the preservation or restoration of the "sensory" function of disrupted ligament, symptoms such as functional instability and muscle weakness may be avoided.^{50, 87}

Regeneration of mechanoreceptors

Another important issue to consider when discussing the significance of proprioception in ACL surgeries is regrowth, or regeneration, of sensory afferents.

Denti et al.³³ studied the fate of mechanoreceptors in torn and reconstructed ACL in animals and humans. The study has involved three specific groups:

Group 1 - Humans with untreated complete ACL tears. (n=20)

Group 2 - Sheep with three types of ACL reconstruction: Bone-patellar-bone graft; Bone-patellar-bone augmented with ligament augmentation device (LAD); Leeds-Keio artificial ligament. (n=12)

Group 3 - Humans with failed ACL (semitendinosus) reconstruction. (n=2)

The results indicated that while morphologically normal mechanoreceptors remained in the torn ligament for 3 months post-injury in Group 1, their number gradually decreased after this time, and that there was a total absence of corpuscles and free nerve endings in lesions that were 1 year old. In Group 2, there was the presence of mechanoreceptors in ACL reconstructions with the autologous patellar tendon grafts. Mechanoreceptors were identified at 3 months and continued to be evident up to 9 months after the procedure. No mechanoreceptors, however, were found when the ACL reconstruction was done with an Leeds-Keio artificial ligament. Group 3, which consisted of two subjects with ACL reconstructions using the semitendinous tendon, demonstrated a significant number of Ruffini and Pacinian corpuscles, especially near the tibial insertion. It should be noted that while the ACL reconstructed knees in Group 3 demonstrated significant laxity during clinical and instrumental testing, neither subject reported episodes of giving way or instability. In addition, during arthroscopy, the semitendinous graft was found to be slack and degenerated. Denti et al.³³ reasoned that the absence of functional instability in Group 3 may be due to the presence of mechanoreceptors found, which may be supplying useful proprioceptive information even in a mechanically nonfunctional graft. Although Denti et al.³³ demonstrated repopulation of mechanoreceptors after ACL autograft reconstruction, whether these sensory receptors recovered their physiological roles was not determined. The absence of mechanoreceptors in those animals with ACL reconstructions using the artificial Leeds-Keio ligament suggests that the use of an artificial ligament is not an appropriate choice for ACL reconstruction.

Other histological studies using experimental animal models have supported the notion that repopulation of mechanoreceptors occurs after ACL reconstruction. Tsujimoto et al.⁸⁸ compared ACL repair with patellar tendon augmentation to excision of the ACL stump with patellar tendon autograft reconstruction in goats. Although more mechanoreceptors were found in the repair and augmentation ligaments, mechanoreceptors were found after both types of surgeries. In the repair and augmentation group, the knee was also more stable, the reconstructed ACL stiffer, and there was improved gait and recovery. Tsujimoto et al.⁸⁸ noted that few if any mechanoreceptors were evident prior to 6 months postoperatively and that the quantity of receptors found after surgery was less than that of the normal ACL. Based on the findings of their study, the investigators concluded there may be value in preserving the remnants of the ACL during surgical reconstruction. The functional significance of this repopulation of mechanoreceptors demonstrated is still currently unknown.

Preservation of the Natural ACL

According to Safran et al.⁸⁷, "the next alternative for promotion of mechanoreceptor function is acute reconstruction of the ACL or other damaged ligaments, with the natural ligament insertion sites attached to the graft." Many studies have found the majority of ACL mechanoreceptors to be located at the insertion sites of the ligament.^{5, 15, 16, 19} Therefore, it is very likely that by preserving the natural ACL insertion stumps, there is great potential for the original ACL mechanoreceptors to transfer their function to the reconstructed ligament if they heal under appropriate tension.⁸⁷ In addition, these natural ACL stumps may provide the ideal environment for the repopulation of mechanoreceptors within the graft. However, a concern with this approach of sewing stump ends into the graft is the risk of developing excessive tissue at the insertions of the graft.⁸⁷

Graft Tension

One final consideration in ACL reconstruction relating to knee proprioception is the tension of the ACL graft.⁸⁷ Since all mechanoreceptors need to be mechanically deformed or loaded to transmit impulses to the central nervous system, surgical

procedures may enhance or restore proprioception indirectly through restoration of appropriate tension of capsulo-ligamentous structures. Proprioception has been demonstrated to be diminished in individuals with knee laxity.⁸⁹

Despite intensive research in this area, the source and the importance of the new population of mechanoreceptors within the ACL grafts are undetermined. It is possible the receptors supply the ACL graft by regrowth, regeneration, growth from the surrounding tissues, dedifferentiation of other cells, or some other mechanism.⁸⁷ Also, it has not yet been demonstrated that these mechanoreceptors actually function. Thus, the enhanced proprioception after ACL reconstruction may be due to training or enhanced functioning of other proprioceptors from sources other than the new ACL. Another unanswered question is how much repopulation is needed in the graft to cause a detectable difference in the functional stability of the operated knee.⁸⁷

Current Literature On the Proprioceptive Function of the ACL

Although the recent studies on the proprioceptive function of the ACL have enhanced our understanding of why surgical reconstructions do not create normal knee function, the question of what are the effects of reconstruction on the proprioceptive function of the involved knee remains. Current research findings on the effects of ACL reconstruction on knee proprioception provide no consensus.^{34, 90, 91} The discrepancy between studies may be due to the different measures of proprioception and/or kinesthesia used, time after surgery, age of the subjects, and different surgical techniques. In addition, the ultimate significance of statistical differences of proprioception as determined in research studies is unknown. Some studies have demonstrated that ACL reconstruction restores proprioception to a sensitivity equivalent to that of uninjured controls.^{90, 91} Others have found that proprioception after ACL reconstruction is better than proprioception of ACL deficient knees, but is still diminished when compared to uninjured controls.^{34, 71} Studies have also found that a proprioceptive deficit exists in the postsurgery knee as compared with the contralateral, uninjured control knee.²⁹ No published studies have compared proprioception in the same subject before and after ACL reconstruction to assess if a loss or gain of proprioception occurs with surgery.

Proprioceptive Studies

Proprioception of the knee has been measured by various methods in the literature. Examples of the proprioceptive measures used in the literature are:

1. Detection of passive motion.
2. Reproduction of passive positioning.
3. Relative reproduction of passive positioning.
4. Static awareness of joint position.
5. Standing balance.

It should be noted that although many of the investigators state that proprioception is being measured when the above methods are used, kinesthesia rather than proprioception is really what is being measured in most cases.

The main purpose of a number of recent studies has been to evaluate the effect(s) of ACL injury and ACL reconstruction on clinical proprioceptive measures.

Corrigan et al.⁶⁹ measured both the ability to reproduce passive positioning and to detect passive motion of the knee joint in individuals with torn ACLs and age-matched controls. When compared to the controls, both the ability reproduce passive positioning and to detect passive motion in the ACL deficient knees were found to be significantly diminished.

Barrack et al.⁴⁰ studied the ability to perceive passive motion of the knee joint in those with arthroscopically proven complete ACL tears and found the ACL deficient limb to have a significantly higher threshold for detecting a change in joint position compared to the normal contralateral knee. In contrast, the control group showed no significant difference in the perception of passive motion between limbs. Based on the popular postulation that muscle afferents play a strong role in kinesthesia, this decline in awareness after ACL injuries may be attributed to a loss of muscle receptor function, secondary to muscle atrophy.^{18, 39, 63} However, multivariate analysis confirmed that the changes observed in kinesthetic awareness of the ACL deficient knee were due to the loss of the ACL rather than other variables such as isokinetic strength, time since injury, and the subject's age. Other studies have also found no correlation between muscle strength and measurements of proprioception.^{70, 71} Results of these studies seem to confirm that the changes observed in knee proprioception after ACL injuries are solely due to the loss of the proprioceptive function of the ACL. However, the relationship between muscle strength and muscle spindle sensitivity is unclear at this point.⁹²

MacDonald et al.⁹⁰ studied the perception of passive motion in three groups of subjects:

1. ACL deficient.
2. Hamstring tendon-ligament augmentation device ACL reconstructions.
3. Bone-patellar tendon-bone ACL reconstructions.

No statistical significant differences were found between the groups. In agreement with Barrack et al.⁴⁰, MacDonald et al.⁹⁰ also found no significant correlation between the threshold of perception of passive movement (TPPM) differences between involved and uninvolved knees and either injury to surgery time interval (ACL reconstructed subjects)

or injury to follow-up (ACL deficient subjects). If the loss of the ACL simply results in a loss of passive restraint that eventually leads to stretching of capsular structures, possibly causing a decrease in the response of capsular receptors and thereby contributing to the loss of proprioception, one would expect a significant loss of proprioceptive ability in chronically but not acutely ACL injured knees.^{40, 90} According to MacDonald et al.⁹⁰, the results of their study lend support to the theory that proprioceptive loss can be a cause of joint laxity and not just the result of it.

Barrett³⁴ studied static awareness of joint position in three groups:

1. Normal knees.
2. ACL deficient knees.
3. ACL reconstructed knees.

In the study, the ACL deficient knees had significantly poorer position sense than the normal and ACL reconstructed knees of age-matched subjects. The normal intact knee had the most accurate static joint position sense. More importantly, clinical assessments of ACL laxity and subjective knee scoring systems were observed to correlate poorly with an individual's satisfaction and the functional capability of the knee. Static awareness of joint position, however, was found to correlate closely with the functional outcome of the knee and an individual's satisfaction with the knee. This may explain why those with insufficient ACLs feel their knees are unstable despite minimal laxity observed in clinical assessments. It may be that after an ACL rupture, proprioceptive sensation must arise from other sources in the knee, such as the collateral ligaments and the joint capsule.^{34, 37} However, because an ACL deficient knee moves in a non-physiological axis, the remaining proprioceptive output is non-physiological and disorganized. Therefore, the individual feels the knee to be unstable due to "cortical interpretation and analysis of knee position that is disturbed."³⁴(p.836) Also, the unphysiological gait of the individual with an ACL deficient knee may cause abnormal loading in the joint and lead to degenerative changes in the long term.³⁴

Using three different outcome measures as indicators of proprioception (reproduction of passive positioning, relative reproduction, and detection of passive of

passive motion), Co et al.⁹³ concluded that a well done ACL reconstruction with appropriate rehabilitation can result in proprioception that is essentially equal to that of the contralateral limb.

Govett⁹¹ observed that static joint position awareness was significantly worse in ACL deficient knees than in ACL reconstructed knees. When compared to the control group, the surgical group was not significantly different in proprioceptive function.

EMG/Reflex Testing

A number of studies have used EMG techniques to evaluate the changes in muscle firing patterns and reflex muscle contraction(s) following ACL injury.^{29, 94-96}

Altered muscle coordination has been observed in those with ACL deficiency.^{97, 98} Higher hamstring moments secondary to altered muscle coordination have been observed in those with ACL insufficiency during functional testing.⁹⁷⁻⁹⁹ It is hypothesized that the observed altered muscle coordination (increased activity of muscles that work synergistically with the ACL) is an essential adaptation to secure knee stability in ACL deficient knees.^{97, 100}

Ciccotti et al.⁹⁴ compared the electromyographic activity of normal, rehabilitated ACL deficient, and ACL reconstructed knees during seven functional activities. The seven functional activities were: walking, ramp ascending, ramp descending, stair ascending, stair descending, running, and cross-cutting. Results indicated the following:

1. Rehabilitation alone for the ACL deficient knee does not restore the EMG patterns of the normal knee during the performance of the seven functional activities, while bone-patella-bone reconstruction does restore the normal EMG synchrony.
2. A greater disparity in performance may be noted between ACL deficient and ACL reconstructed or ACL intact individuals during more strenuous lower extremity activities.

Branch et al.⁹⁹ performed dynamic EMGs in ACL deficient knees and found abnormalities in muscle firing patterns including decreased activity in the gastrocnemius and quadriceps muscle groups and increased activity in the hamstring muscle during stance phase. Branch et al.⁹⁹ also monitored activities with and without bracing and

found that the addition of a derotational brace did not alter the muscle firing pattern in the ACL deficient knee.

Wojtys et al.⁹⁶ assessed the neuromuscular performance in normal and ACL deficient knees. An apparatus delivered an anteriorly directed step force to the posterior aspect of the leg while anterior tibial translation was monitored and EMG signals were recorded at the medial and lateral quadriceps, medial and lateral hamstrings, and gastrocnemius muscles. Testing was done at 30° of knee flexion with the foot fixed to a scale to monitor weightbearing, while the tibia remained unconstrained. The results of the study indicated that timing and recruitment order of the observed muscles were altered by ACL injury. Specifically, those individuals with ACL deficient knees who had higher subjective functional rating scores favored the same voluntary recruitment order as most normals, which was hamstrings-quadriceps-gastrocnemius muscles, while those with lower subjective scores favored their ACL antagonist quadriceps muscle first in their voluntary response. Finally, it was observed that chronic ACL deficient individuals remained slower in their muscle reaction times in all five muscle groups when compared to the normals.

Other investigators have studied the changes in the neuromuscular function of the hamstring muscle after ACL injuries.^{29, 68, 70, 96} Some investigators have suggested the reflex hamstring contraction latency (RHCL) to be a measure of dynamic knee proprioception.^{29, 68} Clinically, RHCL can be defined as the reaction time of the hamstrings to a posterior-anterior force applied to the tibia.²⁹ The measurement of reaction time is one way to quantify the neuromuscular response from the onset of a stimulus to reaction at the muscular level.¹ It is the assumption that as the time lag of the RHCL shortens, the stress to ligaments and other knee joint structures becomes less.¹

In two studies, Beard et al.^{29, 68} measured the RHCL in ACL deficient knees and found the mean latencies in the affected legs were nearly doubled of that in the unaffected legs. No correlation was found between passive anterior-posterior laxity and the frequency of reported "giving-away" of the knee.^{29, 68} There was, however, a significant positive correlation between the RHCL differential and the level of reported

instability. Beard et al.^{29, 68} concluded that the loss of protective reflex between the ACL and the hamstrings in those with ACL deficiency is likely to be a contributing factor in the decreased joint stability experienced by these individuals.⁶⁸

Rehabilitation

Rehabilitation is an important component of both the surgical and non-surgical interventions of ACL injuries. Although there is no universally accepted rehabilitation regime, most agree that the general goals of rehabilitation are to:

1. Develop a strong, mobile, and functionally stable knee capable of withstanding the forces created during activities of daily living (ADL) and sport activities.
2. Minimize the complications of surgery.
3. Minimize the risk of future joint deterioration in the involved knee joint.

Open Kinetic versus Closed Kinetic Chain

A primary concern in the rehabilitation of a newly reconstructed ACL is the amount of strain placed on the graft during therapeutic exercises.^{3, 6, 27, 101} At present, the relationship between graft strain behaviour imposed by exercise and the biological response of the healing graft is essentially unknown.¹⁰² However, if the rehabilitation process is too conservative, many complications such as prolonged knee stiffness, loss of range of motion, and atrophy of the thigh musculature may occur.^{27, 101} As a result of this dilemma, numerous studies have been done to investigate the strain within the ACL during exercises commonly used in rehabilitation.^{38, 41-44, 101, 103-106}

Some investigators have specifically examined the effects of open kinetic chain exercises and closed kinetic chain exercises on the ACL.^{103, 105, 106} Yack et al.¹⁰⁶ found significantly less anterior tibial translation during closed kinetic chain exercises in those with ACL deficient knees than during open kinetic chain exercises. In addition, it was observed that while anterior tibial translation increased with an increase in loading during open kinetic chain exercises, it was not significantly different during closed kinetic chain exercises. Ohkoshi et al.¹⁰⁵ examined the mean shear force exerted on the tibia at 15°, 30°, 60°, and 90° of knee flexion while the subject stood on both legs. The mean shear force exerted on the tibia demonstrated a posterior drawer force at each of the knee flexion angles tested. In addition, shear forces were estimated to be negative in more than 90% of the population in positions with the knee flexed at 30° or more and the trunk anteriorly flexed at 30° or more. Ohkoshi et al.¹⁰⁵ concluded that it would be beneficial

to include closed kinetic chain exercises such as the “half-squats” in the early stages of ACL rehabilitation for the following reasons: (1) to enhance proprioceptive function of the affected lower limb(s), (2) to prevent bone atrophy, (3) it is functional, and (4) to cause simultaneous contractions of the quadriceps femoris muscles and the hamstrings. Therefore, closed kinetic chain exercises are applicable in the early stages after ACL reconstruction when excessive strain to the graft is undesirable.

Accelerated Rehabilitation

Recently, the concept of accelerated rehabilitation after surgery has been proposed and implemented by some investigators to overcome the many complications of ACL reconstructions.^{101, 104, 107} Components of an accelerated rehabilitation program are:

1. No initial range of motion restrictions
2. Weightbearing of the limb as tolerated by the patient
3. Closed kinetic chain exercises
4. Proprioceptive training

Shelbourne et al.¹⁰¹ observed that participants (post ACL reconstruction) of an accelerated rehabilitation program had less anterior knee pain, more knee joint mobility, and better strength in the lower limbs than those on a more conservative program. The study also indicated that the accelerated rehabilitation program did not compromise the integrity of the ACL grafts. Histologic analysis of graft tissue from individuals from both groups failed to indicate any adverse reaction to the physical stresses inherent in the accelerated rehabilitation protocol. MacDonald et al.¹⁰⁴ examined the effects of an accelerated rehabilitation program after ACL reconstructions with combined semitendinosus-gracilis autograft and a ligament augmentation device. Again, no detrimental effects on the ACL reconstructed knees were found. However, opponents of this type of rehabilitation argue that because the relationship between graft strain and the healing response of the graft is currently unknown, it is impossible to safely recommend such exercise programs without running the risk of permanently elongating the graft or disrupting its fixation sites.¹⁰² Regardless, the success of accelerated rehabilitation has been observed in a number of studies.^{101, 104, 107} For example, in the study by

MacDonald et al.¹⁰⁴, 32 of the 34 subjects returned to their pre-injury activity level at approximately 20 to 34 months post-reconstruction.

Proprioceptive Training

There is indirect evidence suggesting that the existing motor programs after an ACL injury can be modified according to the altered sensory situation to regain nearly normal neuromuscular function.^{72, 89, 94, 108, 109} We must remember that although the afferent feedback from the ACL may be important for proprioception and functional joint stability, afferent fibers with sensory endings in the ACL are only a minor part of the total innervation of the knee joint. Thus, it is of interest to determine whether denervation of the ACL secondary to injury or surgery could not be compensated for by the numerous afferent fibers that supply the capsule and other ligaments of the knee joint. These sensory endings can also be activated by forces or movements that cause tension to the ACL.^{76, 77} It has been demonstrated that increasing the tension of the collateral ligaments or the posterior cruciate ligament elicits similar effects on the gamma efferent muscle spindle system.^{76, 77} Thus, these afferents may signal sensory information to the same neuronal circuit(s) the ACL does. However, although the effects of the afferent fibers from the posterior articular nerve of the knee on spinal neurons have been demonstrated in general, little information is available about the relevance of different afferent inputs, from the capsule and the ligaments, to these spinal circuits.²²

Wojtys et al.¹¹⁰ conducted a study to determine the effects of various effects of various exercise regimes (isotonic, isokinetic, and agility) on the muscle reaction time the muscles crossing the knee joint (gastrocnemius muscle, medial hamstring muscle, lateral hamstring muscle, lateral quadriceps, and medial quadriceps). These muscles are capable of knee joint compression and that may ultimately aid the ACL in preventing excessive anterior tibial translation. To measure muscle reaction times, an apparatus delivered an anteriorly directed step force to the posterior aspect of the leg while anterior tibial translation was monitored and EMG signals were recorded. According to the investigators, the importance of muscle reaction times to normal extremities for joint stabilization and injury prevention is unclear. In addition, although weight training is an

important part of most athletic conditioning programs, the effect of these programs on neuromuscular function remains unclear. The study included four groups:

Group I - Healthy volunteers on a isokinetic program.

Group II - Healthy volunteers on a isotonic program.

Group III - Healthy volunteers on an agility program.

Group IV - Controls.

All three training groups exercised for 30 minutes three times per week for 6 weeks. The results indicated that while the agility-trained group generally improved in muscle reaction time in all categories (spinal reflex, intermediate response, and voluntary response), the voluntary response times in the isokinetic group were slower in all five muscle groups, with the medial hamstring and medial quadriceps muscles showing significant delays. The isotonic group's responses showed insignificant changes after 6 weeks of training. Thus, while agility exercises can potentially improve muscle reaction time to anterior tibial translation at the knee joint, isotonic and isokinetic strength training of the lower extremities do not appear to improve this parameter.

Zatterstrom et al.⁷² demonstrated the standing balance of subjects with chronic ACL insufficiency improved with physiotherapy (3 to 6 months), and follow up examination after 36 months proved persistent normalization of the single-limbed balance on both sides (ACL intact and ACL insufficient).

After studying the ability to detect passive joint motion in 12 ballet dancers and 11 age-matched controls, Barrack et al.⁸⁹ concluded that kinaesthetic awareness can be improved through extensive athletic training.

Success after ligament reconstruction, therefore, may not depend directly on the tightness or strength of the reconstruction, but rather on the recovery of proprioception. High levels of athletic performance may elude the individual with a reconstructed ACL due to the loss of proprioceptive nerve-endings, causing a loss of the normal feedback mechanism and reflex postural tone of the muscles.³⁴

As mentioned, the ACL may have a neurophysiological proprioceptive role that is just as important as its mechanical role in maintaining joint stability. Since a decrease in proprioception of the knee can contribute to progressive joint instability, leading to rapid

joint deterioration, the inclusion of proprioceptive training in the rehabilitation of ACL lesions is considered to be beneficial.^{4, 47} The ultimate goal of proprioceptive training is to regain proper neuromuscular control of the affected joint(s).⁴⁷ As part of regaining proper neuromuscular control of the knee joint, dynamic (or reflex) control of the hamstring muscles must be restored.^{29, 68, 70} Walla et al.¹¹¹ observed that high functional rating scores were correlated to the presence of "reflex control" of the hamstrings in individuals with ACL deficient knees. He then concluded that dynamic hamstring control is important in this population. Giove et al.¹¹² found higher levels of sports participation in those whose hamstring strength was equal to or more than their quadriceps strength. Studies also indicate that the RHCL of an ACL deficient knee can be improved through techniques that facilitate rapid hamstring contractions and emphasize the proprioceptive feedback from around the knee. In addition, a positive correlation between improvements in RHCL and functional gain has been observed.^{70, 109} Thus, it appears that a proprioceptive training program for ACL deficient or ACL reconstructed knees should include techniques that will facilitate rapid recruitment of the hamstring muscles.

Despite all the research indicating the importance of proprioception in the function of the knee joint, proprioceptive training protocols in clinical setting still appear to be lacking. Based on the database collected, Beard and Fergusson¹¹³ reported that 72% of the centers surveyed had the main objective of increasing muscular strength for the ACL deficient knee while only 12% had the objective of obtaining dynamic stability via proprioceptive training.

Chapter Three **METHODOLOGY LITERATURE REVIEW**

Kinetic Communicator Dynamometer

Isokinetic dynamometers are frequently used by clinicians and researchers as assessment tools. In order for a measurement tool to be clinically useful, the tool must be considered to be reliable, valid, and sensitive to clinically important changes(s). Reliability is the first prerequisite for validity and sensitivity to change.

The Kinetic Communicator (KIN-COM[®]) dynamometer (Chattex Corp., Chattanooga, TN) system is a hydraulically driven, microcomputer-controlled device for the test, measurement, and rehabilitation of human joint function. The KIN-COM user performs a movement against a resistance which the machine provides via a rotating lever arm system. The machine-controlled movement modes include isokinetic, semi-isotonic, and passive joint motion. The KIN-COM can induce concentric, eccentric, or isometric contraction of the involved muscle(s).

Farrell et al.¹¹⁴ conducted a study to assess the reliability and validity of the KIN-COM device operating system, with the unit operating in a manner designed to imitate human use of the machine. The study focused on the following functions of the unit:

1. The lever arm position.
2. The lever arm velocity.
3. The force measurement systems.

The three functions of the KIN-COM were tested under both static (no lever arm movement) and dynamic (operating) conditions. Measurements made by the KIN-COM system were compared to measurements made simultaneously with external and independent devices designed to copy the KIN-COM's system. The results of the study indicated the following:

1. Average lever arm velocity is within 1.5% of the target velocity.
2. Acceleration time of the lever time to target velocity is within 0.16 seconds (worst case). Deceleration is affected by lever arm direction and not target velocity, and it is equal to approximately 50% of the acceleration time.
3. The force measuring system is within 3% of the actual applied load(s).

Thus, Farrell et al.¹¹⁴ concluded that the KIN-COM is acceptable for most clinical or research applications.

Although the KIN-COM is generally agreed upon as a reliable measuring tool in the literature, there are still some methodological issues that are commonly debated on in the literature. Some of these issues are:

1. What is the most reliable and valid value derived from the KIN-COM to quantify strength?
2. What is the significance of preload?
3. What is the significance of the dynamometer application arm length?
4. What is the significance of having an intercontraction pause?
5. Should data derived from isokinetic tasks be "trimmed" of the nonisokinetic values produced at the extremes of the range of motion?
6. What is the most reliable or clinically relevant test protocol for strength testing?

It is beyond the scope of this thesis paper to discuss all the significant findings in the literature relating to these methodological issues. A brief synopsis, however, will be provided.

Strength Quantification

In a study conducted by Tis and Perrin¹¹⁵, the relationship between average force, average torque, peak force, and peak torque were examined when measuring isokinetic strength of the knee extensor and flexor muscles. Each subject's concentric and eccentric quadriceps femoris and hamstring muscle strength was evaluated at 90°/second, which was performed through the range of 5 to 90 degrees. A preload of 75N was used and data were gravity corrected. The results indicated the following:

1. For knee extensor musculature, r values ranged from 0.82 to 0.94 and 0.91 and 0.99 for concentric and eccentric contractions, respectively.
2. For knee flexor musculature, r values ranged from 0.72 to 0.95 and 0.86 to 0.96 for concentric and eccentric contractions, respectively.

The investigators concluded that the use of any of these isokinetic variables would be appropriate when reporting isokinetic data. However, when using peak and average

measures interchangeably, preload and range of motion must remain consistent between and among subjects.

Preloading

Preloading is the setting of minimal resistance of the lever arm that the muscle must overcome in order to trigger the movement of the arm in the predetermined direction. Preloading assists muscle activation in the initial portion of the isokinetic task.¹¹⁶ Jensen et al.¹¹⁷ conducted a study examining the effect of two preload levels on isokinetic performance of the knee extensors on the KIN-COM. The low preload level was 50N and the high level was 75% of a maximal voluntary isometric contraction (MVIC), performed at the start angles of 100° and 30° of knee flexion. The high preload condition had a significant increase in torque at 1, 5, 10, and 15 degrees concentrically and 1, 5, 10, 15, and 20 degrees eccentrically into the range of motion. In comparing the two preload conditions over the whole torque curve, there was a significant difference in average torque values both concentrically and eccentrically, no significant difference in peak torque in either contraction, and a significant shift in peak torque angle with concentric contractions only. The investigators of this study concluded that a high preload level significantly increases torque production in the beginning of the curve and also the average torque for the entire curve.¹¹⁷

According to Hoens and Strauss¹¹⁶, preloading permits recruitment of motor units and stretch of the series elastic component. This assists in obtaining maximal activation of the muscle(s) earlier in the range of motion of the isokinetic task. Without preloading, submaximal activation of the muscle group is likely during the acceleration phase of the movement. During this phase, motor units would be recruited and the torque produced against the resistance pad of the dynamometer would be less than that produced under maximal isokinetic conditions. Setting the preload at a level that eliminates either a positive or negative inflection at the initiation of an isokinetic task can aid in minimizing the impact artifact and the oscillations resulting from the inertia of the segment, and in producing a true isokinetic strength curve shape.¹¹⁶

Dynamometer Application Arm Length

A key recommendation when using isokinetic dynamometers is that the knee and the dynamometer axes are oriented co-axially. When the knee and the dynamometer axes are oriented co-axially, it is thought that the torque scores recorded by the dynamometer are not affected by the length of the dynamometer application arm.¹¹⁸ Co-axial alignment represents the ideal mechanical situation, facilitates analysis of exercise and test situations, and serves as a basis for comparisons of torques within and between subjects or patients. Kramer et al.¹¹⁸ conducted a study to determine if the length of the dynamometer application arm affected torques during reciprocal concentric-eccentric contraction cycles at 60°/second angular velocity. Healthy subjects were tested using dynamometer application arm lengths corresponding to 33%, 67%, and 95% of the distance from the knee axis to a resistance pad placement that just contacted the dorsum of the foot. Results indicated that the torques produced at the 33% length were approximately 39% lower than those produced at the 67% length, and the torques produced at the 67% length were approximately 10% lower than those produced at the 95% length. The investigators of the study believe that the discrepancy between torque readings at different dynamometer application arm lengths is due to the displacement of the knee axis away from the rotational axis of the dynamometer, such that the two axes were no longer co-axial. According to Kramer et al.¹¹⁸, displacement of the knee axis from the dynamometer axis, such that the subject application arm is longer than the dynamometer application arm, produces a dynamometer torque less than that recorded when the two axes are co-axial. If the knee axis is displaced such that the subject application arm is shorter than the dynamometer application arm, the dynamometer torque will be greater than the recorded under the condition of co-axial alignment. Thus, torque measurement recorded using different application arm lengths are not directly comparable.¹¹⁸

Intercontraction Pause

In the study conducted by Wessel et al.¹¹⁹, the effect of an intercontraction pause on the measurement of isokinetic torque of the knee extensors was examined. A pause of 0.25 or 1.0 second was used. The results indicated that peak and average concentric

torques were greater for the 0.25 second pause compared to the 1.0 second pause. Intercontraction pause had no effect on the eccentric phase of the knee extensors.

Truncating Data

In a study conducted by Hoens and Strauss¹¹⁶, the effect of deleting nonisokinetic phases of movement from isokinetic strength evaluations was examined. While the term "isokinetics" denotes a type of muscular contraction which accompanies a constant rate of limb movement, periods of acceleration and deceleration exist in the context of isokinetic exercise and evaluation. The acceleration and deceleration periods of "isokinetic" exercise/evaluation limit the duration of the period of constant angular velocity in exercises/evaluations with isokinetic dynamometry. According to Hoens and Strauss¹¹⁶, the reliability and validity of the measurement of torque produced by the muscle groups involved in the task is dependent on several factors, including the achievement and maintenance of the preset velocity by both the dynamometer and subject. A technique to correct for measurement error in the extremes of range for isokinetic tasks is to eliminate data generated in these regions from the analysis.¹¹⁶ However, there appears to be no consistency in the portion of the ROM excluded in the literature. In the study conducted by Hoens and Strauss¹¹⁶, the isokinetic strength and endurance of the trunk extensors and flexors in normal male and female subjects were evaluated concentrically from 25° of extension to 30° of flexion at angular velocities of 20, 40, and 60 degrees per second, on two occasions. Full range of motion average torque (FRAT) and truncated range of motion average torque (TRAT) were calculated. The results indicated that direct FRAT and TRAT measures, although highly correlated, were significantly different at each of the three angular velocities. Derived agonist/antagonist ratios had slightly lower correlations and were significantly different from each other at 40 and 60 degrees per second. The investigators of the study concluded that the nonisokinetic phases of an isokinetic task significantly influence trunk average torque recorded by the dynamometer, particularly at faster velocities and with direct measures.¹¹⁶

Standard Protocol

Despite all the research that has been done on isokinetic dynamometry, there is a lack of consensus as to what specific protocol or methodology should be used for strength testing of the particular regions of the body.¹²⁰ Differences in testing protocols, participant characteristics and type of dynamometer do not allow valid comparisons between studies. Some investigators have determined test-retest reliability using average torque, while others have used peak torque values.^{120, 121} Furthermore, the number of trials used to establish average or peak torques differ between studies. In some studies, agonistic and antagonistic movements were assessed separately, while others used reciprocal tests.^{114, 122} Similarly, eccentric and concentric movements were performed separately or in one continuous movement.¹²⁰ Finally, pretest sessions were performed in some studies, while there were no familiarization tests in others.¹²⁰

Reflex Hamstring Contraction Latency

Reflex hamstring contraction latency was first suggested by Beard et al.²⁹ as a dynamic measurement of proprioception. Neuromuscular performance can be assessed at three levels¹¹⁰:

1. Spinal stretch reflex response (M1).
2. Intermediate response (M2).
3. Voluntary or volitional response (M3).

Reflex hamstring contraction latency has been assessed at all three levels in the literature.^{29, 68, 96, 110} In a study conducted by Wojtys et al.¹¹⁰, the neuromuscular performance of normal lower extremities was assessed using EMG. These investigators found the following:

1. The spinal stretch reflex responses of the lower limb occur between 26 and 130 msec after the onset of anterior tibial translation force.
2. The intermediate responses is very reproducible, occurring between spinal stretch reflex and volitional activity. It routinely occurs just before volitional activity at 110 to 216 msec after the onset of anterior tibial translation force.
3. Volitional activity is of the largest amplitude and of longest duration. It occurs between 156 msec to 431 msec after the onset of anterior tibial translation force.

Currently, there are two popular methods of measuring the neuromuscular function of the hamstring muscle, which are:^{1, 68}

1. The Vicon (Oxford Metrics, Oxford, England) Interfaced Knee Displacement Equipment (VIKDE).
2. The Kinetic Communicator (KIN-COM[®]) dynamometer (Chattecx Corp., Chattanooga, TN).

When using the VIKDE to measure reflex hamstring contraction latency, the subject is measured in a position of single-limb stance (full weight-bearing) with the knee flexed 30°. ^{29, 68} An anteriorly directed shear force is applied to the tibia and surface EMGs record the activity of the hamstrings in response to the applied force. The latency of contraction is defined as the time from initial tibial movement, identified by accelerometry, to the onset of increased hamstring EMG activity. When using this

method of assessing the neuromuscular function of the hamstring muscle, all three types of muscular responses (spinal reflex response, intermediate response, volitional response) may be assessed.

There are two methods of measuring RHCL using the KIN-COM.¹ The first method involves measuring peak torque time (PTT). Peak torque time was first defined by Ihara and Nakayama⁷⁰ as the "time before the hamstring exerts maximum force." (p.314) Peak torque time is the time lapse between the initial mechanical movement of the dynamometer lever arm and the generation of maximum torque by the hamstring musculature in response to the sudden forward movement of the dynamometer lever arm. In addition to analyzing PTT, Ihara and Nakayama⁷⁰ also looked at peak torque value (PTV), rising torque time (RTT), and rising torque value (RTV) in their study. Of the four parameters, PTT seems to be the most important parameter representing hamstring reaction time. The second most important parameter of reaction time seems to be the RTT because it represents the time the hamstrings are about to react. All these parameters are considered to be volitional responses of neuromuscular function.

The second method of measuring hamstring reaction time using the KIN-COM isokinetic dynamometer is electromyograph time (EMGT).¹ Electromyograph time measures the time lapse between the initial mechanical movement of the dynamometer lever arm and the first myoelectrical hamstring activity that is recorded.¹

In both methods of measuring hamstring reaction time using the KIN-COM, the subject sits on the table of the KIN-COM with 90° of hip flexion and 90° of knee flexion and is stabilized at the waist and distal thigh.¹ The dynamometer lever arm is secured to the subject's testing leg, 2 cm above the medial malleolus, and it moves unexpectedly forward (into full knee extension) at a angular velocity of 230°/second.^{1a} The subject is instructed to draw the leg backward against the forward force of the lever arm as quickly as possible once the movement of the lever arm is felt.

^a Ihara and Nakayama⁷⁰ used a speed of 210°/second, which is just below the maximal angular velocity of knee flexion during normal gait.

Small et al.¹ did a comparative study on the two methods of measuring RHCL using the KIN-COM isokinetic dynamometer in the normal population. Based on the results of the study, both the PTT and EMGT are reliable methods for measuring hamstring reaction time (Table 3.1).

Table 3.1: Cronbach Coefficient Alpha for Two Methods of Measuring Reaction Time in the Dominant and Nondominant Hamstring Musculature¹

Method	Dominant	Nondominant
Peak Torque Time	0.82	0.90
Electromyograph Time	0.90	0.86

However, due to the sensitivity of the EMGT, there are some difficulties associated with anticipation of the lever arm. Anticipation of the lever arm can be identified by an increase in myoelectrical activity prior to actual lever arm movement.¹ According to Small et al.¹, this heightened pre-stimulus EMG activity can not be accurately differentiated from EMG activity representing actual response to lever arm. Consequently, full subject compliance is essential for obtaining accurate measurements using the EMGT protocol.

In their study, Small et al.¹ also attempted to determine if there is a significant difference in RHCL between dominant and nondominant limbs. The study found no significant difference ($p < 0.05$) in reaction time as measured by PTT and EMGT between the dominant and nondominant limbs (Tables 3.2 and 3.3). The authors concluded that the uninvolved lower extremity may be used as a control.

Table 3.2: Mean Hamstring Reaction Time as Measured Using PTT (N=40)¹

Leg	Mean (msec)	SD	Range
Dominant	380.5	35.9	130-500
Nondominant	394.1	45.5	260-500

Table 3.3: Mean Hamstring Reaction Time as Measured Using Electromyograph Time (N=40)¹

Leg	Mean (msec)	SD	Range
Dominant	30.5	1.41	10-120
Nondominant	33.6	1.94	10-150

Wojtys et al.¹¹⁰ reported a lack of correlation between muscle reaction time assessed by EMG and the time to peak muscle torque. They concluded both parameters

depend on neural pathways and occur sequentially. Also, the investigators felt that both parameters appear to be needed for effective limb protection but seem to be affected by different training factors. It should be noted, however, the method in which PTT was measured by Wojtys et al.^{96, 110} is different from that described by Small et al.¹.

Functional Testing

Functional tests are often included in the evaluation of anterior cruciate ligament deficiency or are used as a method to monitor rehabilitation.^{97, 123-127}

Barber et al.¹²⁶ studied the effectiveness of five various hopping, jumping, and cutting type tests in determining lower extremity limitations in ACL deficient knees. The study involved 93 subjects with ACL intact knees and 35 subjects with ACL deficient knees. The five functional tests were: (1) one-legged single hop for distance, (2) one-legged vertical jump, (3) one-legged timed hop, (4) shuttle run without pivot, and (5) shuttle run with pivot. For each functional test, the limb symmetry index was calculated. To calculate the symmetry index for the one-legged single hop for distance and the one-legged vertical jump, the mean of the involved limb is divided by the mean of the noninvolved limb and the result is multiplied by 100. To calculate the symmetry index for the one-legged timed hop and the two shuttle runs, the mean of the noninvolved limb is divided by the mean of the involved limb and the result is multiplied by 100. In the normal population, no statistical significance was found between right and left lower limb scores (limb symmetry index) as related to sports activity level, gender, or dominant side.¹²⁶ This allowed an overall symmetry index score to be established for the normal population as a whole. The majority (92% to 93%) of the normal population scored in the 85% limb symmetry category for the one-legged single hop for distance and the one-legged timed hop. The study found that neither the two shuttle run tests nor the vertical jump test are useful in detecting lower limb functional limitations. More than 90% of the ACL deficient population scored in the normal limb symmetry range on the two shuttle run tests; subjects tended to compensate by running at one-half velocity and guarding both legs during turning and cutting maneuvers. For the vertical jump test, 27% of normal subjects scored outside the normal limb symmetry range. It is the recommendation of the authors that at least two hop tests are used when assessing functional limitations in the ACL deficient population.¹²⁶ This is because while 60% of the ACL deficient knees performed abnormally on at least one of the two hop tests in the combined test analysis, the range of abnormality decreased to 42% or 50% (depending on the test used) if only one hop test was used.

Noyes et al.¹²⁷ studied the sensitivity of four different types of one-legged hop tests. The four one-legged hop tests were: (1) single hop for distance, (2) timed hop, (3) triple hop for distance, and (4) cross over hop for distance. The analysis showed that 62% of the ACL deficient population performed abnormally on at least one of the two hop tests conducted. When only one test was conducted, the percentage of abnormal results decreased to between 49% and 52%. The authors concluded that these hop tests have a low sensitivity rate. However, the high specificity and low false-positive rates allow these hop tests to be used as confirmation tests for lower limb dysfunction.¹²⁷

In a study conducted by Kramer et al.¹²⁸, the test-retest reliability of the single hop for distance test following ACL reconstruction was examined. According to the investigators of this study, in documenting the single hop for distance, the criterion measurement has been calculated using the mean distance of three hops and that of the longest hop. Whether the three hops are equivalent, and both data analysis strategies lead to similar scores, or whether using the longest hop leads to significantly higher scores than using the mean of three hops, is unclear. The primary purpose of the study was to determine test-retest reliability of the single hop for distance, when using the distance hopped on each leg and the hop index as criterion measurements, and using the two-data analysis strategies:

1. The mean of three hops.
2. The longest of three hops.

Each test occasion (two in total, within a 5-day interval) consisted of three trials for each leg. The mean distance of the three hops and that of the longest hop were determined (in cm) for each leg. The mean hop index score was determined by dividing the mean distance hopped on the involved leg by that hopped on the noninvolved leg, and the longest hop index was determined by dividing the longest hop on the involved leg by the longest hop on the noninvolved leg. Results of the study demonstrated acceptable reliability for the distance hopped on each leg and the hop index, regardless of whether the mean of three hops or the longest hop was used in calculations (all ICC>0.75). Although hop distances calculated using the longest hop were significantly greater than those determined using the mean of three hops, hop indexes were not affected by data

analysis strategy. The percentage difference between the scores determined on occasion one and occasion two averaged approximately 3%. This indicates that any learning component associated with performing the single hop for distance is minimal and is not manifested by a systematic tendency for improvement simply as a result of repeating the test. As a result, researchers can have confidence in the data generated on one occasion.

Booher et al.¹²⁹ conducted a study examined the reliability of the following single-leg hop tests in healthy subjects:

1. Hop for distance.
2. Six meter timed hop.
3. Thirty meter agility hop.

Healthy subjects chose a random sequence of testing that was performed on both lower extremities. Subjects performed two testing trials for each single-leg hop test on each occasion. An independent t-test revealed no significant difference between dominant and nondominant extremities for all three dependent variables. An ANOVA repeated-measures analysis revealed significant differences between the test trials within and between sessions for all three dependent variables. The fact that the test scores were consistently improving during the second trial of each day indicated that motor learning was occurring. However, when the mean of two test trials was analyzed, no significant difference existed between two (hop for distance and timed hop) of the three dependent variables. By taking the mean of the two trials for each day and comparing days, the investigators obtained greater stability of measures as demonstrated by the intraclass correlation coefficient, standard error of measurement, p value, and confidence interval. Although the agility hop was still significantly different between test days, Booher et al.¹²⁹ felt it was still a stable measure for clinical usage because:

1. The 95% confidence interval was 15.05 to 18.07 seconds. This is considered to be a small confidence interval.
2. When the difficulty of a 30 meter single-leg agility hop test is considered, a standard error of measurement of 0.77 seconds and a mean difference of 0.47 seconds between occasions are very small.

Thus, the investigators of this study concluded that the three single-leg hop tests examined were reliable and contained small measurement error as performed in the study.

Subjective Scoring Scales

The most commonly used subjective scoring scale for ACL lesions is the modified Lysholm and Gillquist Knee Scoring Scale (1985).¹³⁰ The original version was first introduced in 1982.¹³¹ The maximum score in which a subject can achieve on this scoring scale is 100 (maximum function). The intrapersonal coefficient of variation of this scale is 3% and the interpersonal is 4%.¹³⁰ The test-retest correlation coefficients are 0.97 and 0.90 respectively.¹³⁰

The Tegner and Lysholm Activity Score (1985) is graded from 0 to 10 and covers activities in daily life and recreational and competitive sports.¹³⁰ In a study by Tegner and Lysholm¹³⁰, significant differences in scores (modified Lysholm and Gillquist Knee Scoring Scale) at different activity levels were obtained in those with ACL deficient knees. For example, the mean score for subjects at activity levels 5-10 was 83 ± 10 , and for subjects at activity level 0, it was 53 ± 16 ($p < 0.001$).¹³⁰ The authors argued that the activity scale is a "valuable complement to the functional score because limitations in knee function may be masked by an involuntarily low activity level."¹³⁰

Chapter Four

DEFINITION OF TERMS

1. ACL deficient: A condition which the ACL has been ruptured and it has not been surgically repaired or reconstructed.
2. ACL reconstruction: A surgical procedure which attempts to restore the integrity and function of the ruptured ACL.
3. Isolated ACL rupture: A complete tear of the ACL that is not associated with other ligamentous, capsular, meniscal or bony injury.
4. Functional joint stability: The condition in which the joint is stable and does not give symptoms during physical activities.
5. Proprioception: The unconscious sensation of joint movement and joint position. Proprioception is involved in the control of movement and posture.
6. Kinesthesia: The conscious sensation of joint movement and joint position. Kinesthesia is involved in the control of movement and posture.
7. Isokinetic: The dynamic muscular contraction when the velocity of movement is controlled and maintained constant by a special device.
8. Concentric muscle contraction: A muscle contraction that involves the approximation of the origin and insertion of the muscle.
9. Eccentric muscle contraction: A muscle contraction that involves the origin and insertion of the muscle to move away from each other.
10. Coordination: Highly skilled multimuscular automaticity.
11. Balance: It is the bodily equilibrium or the ability to maintain the center of body mass over the base of support without falling.
12. Engram: Automatic motor patterns.

Chapter Five

PILOT STUDY

Purpose

A pilot study was conducted to determine the test-retest reliability of measuring peak hamstring torque time. The protocol described by Small et al.¹ was used. In the study conducted by Small et al.¹, the main purpose was to determine if there was a significant difference between two methods of recording hamstring PTT using the KIN-COM isokinetic dynamometer (peak torque time vs. electromyograph time). Although Small et al.¹ provided evidence that measuring PTT using the KIN-COM is reliable within an occasion, the test-retest reliability between occasions was not addressed. Unless the test-retest reliability between occasions of an equipment is determined, clinical and research decisions based on the data collected (from the equipment) may be questionable. For instance, an improvement in a subject's scores may be the result of learning to perform better with the equipment, decreased apprehension, and/or simple variation attributable to repeated testing, rather than treatment effect. In addition, in the two studies that used the KIN-COM to assess hamstring neuromuscular function, two different velocities were used for the forward movement of the lever arm, 230°/second and 210°/second. At present, it is unclear whether PTT measured at different velocities may be compared to each other. Therefore, before valid comparisons may be made between results of different studies, it must be shown that there are no significant differences between PTT measured at different velocities. It is also beneficial to determine whether or not we can accurately predict peak torque times at high velocities from those times assessed at lower velocities. At present, the maximum angular velocity that the KIN-COM used for this study can be programmed for is 250°/second. Although this angular velocity appears to be high, it is just slightly above the velocity of the knee extending during the stance phase of the gait cycle. The quadriceps fires during the last 12% of the gait cycle preparing the limb for weight acceptance, and during this time the knee normally extends at a rate of 233° per second.¹³²

Subjects

Six subject, 4 females and 2 males, were recruited from the university population for this pilot study. Informed consent was obtained for all subjects involved in this pilot study. Only subjects without a history of bilateral lower extremity pathology were eligible to participate in the study. A brief interview revealed that all subjects engaged in recreational or competitive sports activities at least three times per week. All individuals involved in the pilot study were right dominant.

Table 5.1 summarizes the descriptive characteristics of subjects involved in the pilot study.

Table 5.1: Descriptive Data for Pilot Study

	N	Minimum	Maximum	Mean	Standard Deviation
Age (year)	6	23.98	29.88	25.88	2.18
Height (cm)	6	156.10	193.40	170.00	13.73
Weight (lbs)	6	108.00	171.60	135.20	21.50

Methods

Forward lever arm movement of the KIN-COM isokinetic dynamometer provided the unanticipated stimulus that evoked an eccentric response of the hamstring muscles. There were two test occasions for each subject. In the first test occasion, three different velocities were used for the forward (extension) movement of the lever arm: 230°/second, 210°/second, and 190°/second. In the second test occasion, only 190°/second was used. A backward (flexion) angular velocity of 10°/second was used for all testing occasions.

All testing occasions occurred at the Allan McGavin Sports Medicine Clinic. Prior to actual testing, all subjects were required to complete 10 minutes of stationary bicycling. This was followed with five repetitions of static hamstring stretch, each held for 20 seconds. Efforts were taken to ensure the subjects had a thorough understanding of the testing procedure. All orders of testing were randomized by side and forward angular velocity of the lever arm for the first test occasion. The order of testing from the first test occasion was duplicated for the second test occasion.

Each subject was seated on the KIN-COM with their pelvis and tested thigh secured to the bench. The subject's trunk was also comfortably, but firmly, strapped to the back of the KIN-COM bench seat. The axis of motion of the KIN-COM was aligned with the lateral femoral condyle of the tested knee. The dynamometer lever arm was secured to the subject's testing leg 2 cm above the medial malleolus. All tests were performed between 0 and 90 degrees of knee flexion. Gravity compensation was performed for all test occasions. A low acceleration rate was used for all test occasions.

Subjects were asked to close their eyes and were fitted with earphones. The music used ranged from classical music to classic rock. The purpose of this procedure was to eliminate any visual or audio cues.

Once a subject was secured to the KIN-COM bench and all visual or audio cues were removed, the subject was allowed four practice trials. After a one minute rest interval, actual testing began.

Test Occasion One

For the first test occasion, six trials were performed at each angular velocity. There was a five minute rest interval between each velocity test session. Thus, there were three test sessions in the first test occasion for each of the lower extremity. Subjects were instructed to maximally contract their hamstring muscle in response to forward lever arm movement. This was achieved by pulling back into the lever arm pad which was moving forward into full knee extension. Subjects were asked to completely relax their musculature after the lever arm achieved full extension and to refrain from anticipating future lever arm movement. Time of lever arm movement was varied according to the following intervals: 5, 3, 8, 6, 5, and 8 seconds between repetitions. This was done to minimize the subjects' tendency to anticipate the forward movement of the lever arm.

Test Occasion Two

For the second test occasion, six trials were performed at 190°/second. Thus, there was only one test session in the second test occasion for each of the lower extremity. After much contemplation and discussion, 190°/second was chosen as the angular velocity to be used in this thesis project to assess time to hamstring peak torque. Therefore, the test-retest reliability of 190°/second needed to be known. The angular velocity of 190°/second was chosen for the following reasons:

1. All potential subjects will have had their ACL reconstructed with their semitendinosus (part of the hamstring muscles). It is quite likely that the affected hamstring group will be under neurological inhibition during the window of time subjects will be involved in study. Therefore, when using velocities such as 230°/second, we may not allow enough time for the affected hamstring group to reach potential peak torque.
2. If we assume that the ACL does contribute to knee proprioception and kinesthesia, then we also must assume that the potential subjects will have impaired knee proprioception and kinesthesia. Thus, we need to ensure that the angular velocity we choose to assess time to hamstring peak torque will provide a large enough window of time for peak torque to be reached and still be challenging for the subjects.
3. To decrease the likelihood of sustaining a strain to the hamstring muscles.

Otherwise, the procedures used in the first test occasion were reproduced exactly for the second test occasion.

Time to peak torque was obtained from ASCII files saved from the KIN-COM isokinetic dynamometer. The slowest and the fastest times to hamstring peak torque were eliminated from each test session for each subject. The mean of the remaining four trials was used as the time to hamstring peak torque for each subject.

Statistics

The criterion score (peak torque time of the hamstring muscle) used for statistical analysis was the mean of the four trials retained from the six trials completed during one test session. Peak torque values used in statistical analysis were also obtained in the same manner as the peak torque time values.

For test occasion one, a repeated-measures analysis of variance was conducted to determine if there were any differences between peak torque times assessed at the three isokinetic velocities. Pearson product-moment correlation coefficients were calculated to determine the relationship of peak torque times measured at the three isokinetic velocities. Regression was then performed to determine the accuracy of peak torque times obtained at lower isokinetic velocities in predicting those obtained at higher velocities.

For test occasion two, intraclass correlation coefficients were calculated to determine the reliability of measuring peak hamstring torque times at the angular velocity of 190° per second between occasions.

The level of significance for all statistical tests were set at $p \leq 0.05$.

Results

Test Occasion One

The main purpose of the first test occasion was to establish the validity of comparing peak torque times collected at different velocities as well as their correlational and regression relationship.

The following table summarizes the descriptive statistics for test occasion one.

Table 5.2: PTT Data for Test Occasion One (msec)

Velocity	N	Minimum	Maximum	Mean	Std. Deviation
Right-190°/sec	6	360.00	480.00	445.83	43.32
Right-210°/sec	6	380.00	467.50	423.75	31.01
Right-230°/sec	6	365.00	442.50	403.75	29.74
Left-190°/sec	6	427.50	522.50	471.58	35.43
Left-210°/sec	6	387.50	512.50	424.17	45.65
Left-230°/sec	6	370.00	475.00	408.75	39.65

The results obtained in test occasion one of the pilot study for hamstring peak torque times at 230°/second coincide with the values Small et al.¹ found in their study. Small et al.¹ found peak torque time values of $\bar{X} = 380.5 \pm 35.9$ milliseconds (dominant leg) and $\bar{X} = 394.1 \pm 45.5$ milliseconds (nondominant leg).

It appears from the descriptive data that peak torque of the hamstring muscle was achieved faster by the subjects as the forward angular velocity of the lever arm was increased. Dietz et al.¹³³ showed that the latency of muscle contraction after perturbation depends on the rate and amplitude of acceleration, and therefore on the force. In their study, Dietz et al.¹³³ examined the electromyogram responses of the leg musculature and the corresponding joint movements following a perturbation of the limb during walking on a treadmill, produced by a randomly timed treadmill acceleration impulse, either predictable, or unpredictable in its amplitude and rate of acceleration. The investigators found that the onset latency (of the gastrocnemius) muscle was shorter (65ms) for high accelerations and longer (85 ms) for lower accelerations. Although the KIN-COM enables the user to select a low, medium, or high acceleration rate, little information is available regarding what these settings exactly mean. After analyzing the ASCII files, it appears that although a low acceleration rate was selected for all test

sessions and occasions, each of the three velocities had a different acceleration rate. Data in Table 5.3 demonstrate that as the forward angular velocity of the lever arm was increased, the acceleration rate also increased. Specifically, data in Table 5.3 indicates that in a given period of time (i.e. 0.08 seconds), the lever arm achieved a higher angular velocity when the preset velocity was 210°/second (or 230°/second) than when the preset velocity was 190°/second. Similarly, the lever arm traveled a greater angular displacement in a given amount of time when the preset velocity was 210°/second (or 230°/second) than when the preset velocity was 190°/second.

Table 5.3: Descriptive Data of Different Preset Velocities

Velocity of Lever Arm	Velocity at 0.08s	Angle at 0.08s (From 90°)	Velocity at 0.10s	Angle at 0.10s (From 90°)
190°/second	116.29°/sec	87.04°	154.46°/sec	84.12°
210°/second	128.54°/sec	86.62°	171.04°/sec	83.42°
230°/second	140.58°/sec	86.12°	187.25°/sec	82.75°

Thus, the tendency for the hamstring muscle to achieve peak torque faster as the forward angular velocity of the lever arm was increased may be explained by the findings of Dietz et al.¹³³.

The data in Table 5.2 suggest that there was a tendency for the dominant limb to respond slightly faster than the nondominant limb. However, a repeated-measures ANOVA found insignificant differences ($p < 0.05$) in PTT between the lower extremities at all three isokinetic velocities.

Table 5.4 summarizes the repeated-measures ANOVA conducted to determine if there were significant differences between peak torque times measured at the three different isokinetic velocities.

Table 5.4: PTT at Three Different Angular Velocities
Tests of Within-Subjects Effects (RM ANOVA)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Sessions @ 190°, 210°, & 230°/sec	17092.10	2	8546.05	30.582	.000
Session * Side	1093.35	2	546.67	1.956	.168
Error (Session)	5588.89	20	279.44		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Side	971.361	1	971.361	0.258	.622
Error	37581.111	10	3758.111		

As indicated by the results, the peak torque times measured at the three different velocities were significantly different. As mentioned previously, there was no significant difference in PTT measured between the left and right lower limbs. Also, there was no significant interaction between isokinetic angular velocity and the side (dominant or nondominant) of limb being tested.

Table 5.5 summarizes the correlations between the three different velocities used to assess time to hamstring peak torque at test occasion one.

Table 5.5: Pearson Product-Moment Correlation Coefficients for Test Occasion One

Variable		Right-190°/sec	Right-210°/sec	Right-230°/sec	Left-190°/sec	Left-210°/sec	Left-230°/sec
Right-190°/sec	r	1.000	.761*	.626	.763*	.577	.579
	Sig. (one-tailed)	.	.039	.092	.039	.115	.114
	N	6	6	6	6	6	6
Right-210°/sec	r	.761*	1.000	.880*	.706	.803*	.782*
	Sig. (one-tailed)	.039	.	.010	.059	.027	.033
	N	6	6	6	6	6	6
Right-230°/sec	r	.626	.880*	1.000	.394	.459	.541
	Sig. (one-tailed)	.092	.010	.	.220	.180	.134
	N	6	6	6	6	6	6
Left-190°/sec	r	.763*	.706	.394	1.000	.877*	.861*
	Sig. (one-tailed)	.039	.059	.220	.	.011	.014
	N	6	6	6	6	6	6
Left-210°/sec	r	.577	.803*	.459	.877*	1.000	.933**
	Sig. (one-tailed)	.115	.027	.180	.011	.	.003
	N	6	6	6	6	6	6
Left-230°/sec	r	.579	.782*	.541	.861*	.933*	1.000
	Sig. (one-tailed)	.114	.033	.134	.014	.003	.
	N	6	6	6	6	6	6

* Correlation is significant at the 0.05 level (1-tailed).

** Correlation is significant at the 0.01 level (1-tailed).

As demonstrated by the data in Table 5.5, the correlation between 190°/degrees and 210°/degrees, and between 210°/degrees and 230°/degrees were statistically significant for both lower extremities. Although it is evident that all three velocities for

the left leg were strongly correlated, the degree of association was still stronger between 190°/second and 210°/second, and between 210°/second and 230°/second, than between 190°/second and 230°/second. The lack of significant correlation found between 190°/second and 230°/second for the right lower extremity may be explained by the findings of Small et al.¹. In their study, Small et al.¹ found the reliability of the PTT protocol was 0.82 and 0.90 for the dominant and nondominant limb, respectively. Thus, the lack of correlation found between 190°/second and 230°/second for the right lower extremity may be due to the decreased reliability of the dominant limb (compared to the nondominant limb) and the small sample size used in this pilot study.

The following table summarizes the regression analysis of test occasion one.

Table 5.6: Regression Analyses for Test Occasion One

Side	Independent Variable	Dependent Variable	Significance of Regression ANOVA
Right	190°/second	210°/second	0.079
Right	190°/second	230°/second	0.184
Right	210°/second	230°/second	0.021
Left	190°/second	210°/second	0.022
Left	190°/second	230°/second	0.028
Left	210°/second	230°/second	0.007

From the data collected, it is evident that peak torque times measured at lower isokinetic velocities were predictive of those measured at higher velocities for the left lower extremity (the nondominant limb). However, only those peak torque times measured at 210°/degrees were predictive of those measured at 230°/second for the right lower extremity (the dominant limb).

Figure 5.1
Regression Analysis for Right 190°/s and 210°/s

Figure 5.2
Regression Analysis for Right 190°/s and 230°/s

Figure 5.3
Regression Analysis for Right 210°/s and 230°/s

Figure 5.4
Regression Analysis for Left 190°/s and 210°/s

Figure 5.5
Regression Analysis For Left 190°/s and 230°/s

Figure 5.6
Regression Analysis For Left 210°/s and 230°/s

Test Occasion Two

The main purpose of the second test occasion was to establish the test-retest reliability (between occasions) of measuring hamstring peak torque time at the isokinetic angular velocity of 190°/second using the protocol described by Small et al.¹. For the second test occasion, only five of the six original subjects returned. Therefore, the sample for the second test occasion consisted of three females and two males.

Table 5.7: Comparison of PTT and Peak Torque (@ 190°/sec) Between Test Occasions

Variable	N	Minimum	Maximum	Mean	SD
PTT @ Occasion One-Right (ms)	5	360.00	480.00	442.50	47.57
PTT @ Occasion Two-Right	5	395.00	480.00	455.00	34.46
Peak Torque @ Occasion One-Right (Nm)	5	38.75	130.50	69.20	39.10
Peak Torque @ Occasion Two-Right	5	39.50	131.25	77.50	35.25
PTT @ Occasion One-Left	5	427.50	522.50	469.40	39.15
PTT @ Occasion Two-Left	5	420.00	485.00	460.00	30.26
Peak Torque @ Occasion One-Left	5	36.75	131.00	60.40	39.87
Peak Torque @ Occasion Two-Left	5	28.75	142.75	67.05	44.29
Time Interval From Test Occasion One to Test Occasion Two (week)	5	12.00	25.00	18.60	5.22

Reliability coefficients were calculated using the intraclass correlation coefficient. The reliability coefficient describes the degree to which scores on a measure represent something other than measurement error.¹³⁴

Table 5.8: Intraclass Correlation Coefficients

Variable	Intraclass Correlation Coefficient (3,k)
Right - PTT (ms)	0.922
Left - PTT	0.901
Right - Peak Torque (Nm)	0.986
Left - Peak Torque	0.984

The reliability of the PTT protocol used in the pilot study was 0.92 and 0.90 for the right (dominant) and the left (nondominant) limb, respectively. The reliability of peak torque was 0.99 and 0.98 for the right and the left limb, respectively.

Conclusion

Based on the findings of test occasion one, comparisons between PTT measured at different velocities should not be made. Based on the Pearson product-moment correlation coefficients calculated in this pilot study, there is a strong relationship between peak torque times measured at 190°/second and those measured at 210°/second, and between peak torque times measured at 210°/second and those measured at 230°/second. Also, it appears that the degree of association between PTT measured at different velocities decreases as the isokinetic velocities become farther apart. Based on the regression analyses, the ability to predict the PTT of a high isokinetic angular velocity from a lower isokinetic angular velocity appears to be dependent on dominance. Similar to the trend observed in the correlational analyses, the ability to predict peak torque times of higher velocities diminishes as the isokinetic velocities become farther apart. Therefore, volitional peak torque times measured at more widely separated isokinetic velocities are less predictive of each other.

Based on the results of test occasion two, the reliability of measuring peak hamstring torque time at the isokinetic angular velocity of 190°/second is 0.92 and 0.90 for the dominant and the nondominant limb, respectively.

Chapter Six

METHODOLOGY

Purpose

Both strength training and proprioceptive training have been emphasized in the literature as important components of the rehabilitation process after ACL injuries. Although the effectiveness of strength training is well-established in the literature, the effectiveness of proprioceptive training is not. In addition, the effects of strength training on neuromuscular function has been examined in the literature while little has been done to examine the effects of proprioception training on strength.

Since an ACL injury often results in decreased function of the involved knee joint, despite restoration of normal joint arthrokinematics via surgical intervention, it is important to optimize factors during the rehabilitation phase, such as strength and proprioception, that may positively influence the present and future function of the individual. Thus, the effectiveness of rehabilitation in restoring these factors must be determined. Numerous investigations have examined the effects of ACL injuries on knee proprioception, but very few prospective studies have been done to examine the effectiveness of proprioceptive training after ACL injuries.

Thus, the main objective of this study was to determine the effectiveness of proprioceptive training versus strength training in restoring the normal neuromuscular function of the ACL reconstructed knee, or specifically, the peak torque time of the hamstring muscle. The second objective of this research was to determine the relative contribution of isokinetic strength and peak hamstring torque time to the performance of two functional hop tests.

The following hypotheses were tested in this study:

H11: The strength training group will demonstrate significantly greater strength gains in the ACL reconstructed knee than the proprioceptive training group at the end of the 12 weeks.

H12: The proprioceptive training group will demonstrate greater improvements in peak torque time of the ACL reconstructed knee compared to the strength training group at the end of the 12 weeks.

H13: The proprioceptive training group will demonstrate greater improvements in the performance of the two functional hop tests on the ACL reconstructed knee compared to the strength training group at the end of the 12 weeks.

H14: The proprioceptive training group will demonstrate greater improvements in the subjective scores compared to the strength training group at the end of the 12 weeks.

H15: Peak torque time will have a significant effect on the performance of the two functional hop tests.

H16: Isokinetic strength will have a significant effect on the performance of the two functional hop tests.

Subjects

Ten subjects who all had their disrupted ACL reconstructed by two orthopaedic surgeons of the Allan McGavin Sports Medicine Clinic were recruited for this study. The total number of subjects needed for the study were determined by power analysis (Appendix A). Due to ethical considerations, a control group was not established for this study. All potential subjects were initially contacted by mail. A list of potential subjects was obtained from the two orthopaedic surgeons who have agreed to work with this study. Subjects were selected based on the following criteria:

1. Individuals who were 18 to 38 years old.
2. Only one knee was involved.
3. An isolated ACL injury that had been surgically reconstructed. (Isolated ACL injury = the collateral ligament(s) did not require surgical intervention and the meniscus (or menisci) was not completely removed)
4. A minimum of 6 months since the date of operation.
5. No previous history of significant injury to or pathology in the ACL reconstructed knee.
6. No significant secondary damage to the involved knee joint as a result of chronic ACL deficiency. (Significant secondary damage = the collateral ligament(s) required surgical intervention and the meniscus (or menisci) was completely removed)
7. Normal hip and ankle joint function.
8. No neurologic diseases.
9. No vestibular or visual disturbances.
10. No arthritic condition(s) involving the lower extremities.
11. Was not attending physiotherapy sessions (within the last 6 weeks).
12. Possessed full range of motion (both active and passive) in the operated knee.
13. Was able to participate in light recreational activities without inducing significant pain or obvious swelling in the operated knee. (Light recreational activities = cycling, swimming, walking)
14. The absence of pain and swelling in the operated knee during normal ADL.

Individuals were excluded if they had received intense proprioceptive training post ACL reconstruction. Individuals were also excluded if they had any cardiovascular, respiratory, systemic, metabolic condition limiting exercise tolerance. Prior to participating in the study, the subjects were required to read and fill out the informed consent form. Once informed consent was obtained, subjects were asked to fill out a subject information sheet designed for this study (Appendix B).

Ethical approval was acquired from the Committee on Human Experimentation of the University of British Columbia. Subjects were withdrawn from the study if negative effects (such as pain and swelling in the ACL reconstructed knee) induced by the experimental protocol persisted after 48 hours or were made worse with subsequent exercise sessions. However, no subjects were withdrawn from the study secondary to persisting pain or swelling in the ACL reconstructed knee.

The 10 subjects were randomly assigned to one of two experimental groups. Group One (Strength Training Group = ST Group) consisted of five subjects who were placed on a general lower limb strength training program (Appendix C). Group Two (Proprioceptive Training Group = PT Group) consisted of five subjects who were placed on a proprioceptive training program^b that had a special emphasis on facilitating rapid hamstring contractions (Appendix C).

Group One (ST Group) consisted of three males and two females with an average age of 24.66 years, who had undergone surgical reconstruction for an isolated unilateral ACL rupture (three right, two left). The subjects in Group One were involved in the following sports prior to their ACL injury: soccer, varsity volleyball, ice hockey, rugby, and hiking. Group Two (PT Group) consisted of one male and four females with an average age of 25.04 years, who also had undergone surgical reconstruction for an isolated unilateral ACL rupture (three right, two left). The subjects in Group Two were involved in the following sports prior to their ACL injury: judo (national level), karate, soccer, varsity ultimate, and squash.

^b If we consider the definitions of proprioception and coordination, it is probably more correct to state that subjects in Group Two were placed on a coordination training program. However, for the purpose of this thesis, the term "proprioceptive training" is used.

All subjects were asked to perform the assigned exercises three times a week. All subjects were asked to come to the University of British Columbia campus three times a week, each time for approximately one hour, to perform their exercises under the supervision of the investigator(s). In some instances, the exercise sessions took place off campus, at locations more convenient for the subjects. Details of each exercise session for all subjects were recorded on a data sheet designed for this study. In addition, all subjects were asked to keep a record of all other physical activities they are involved in for the duration of the study. The main purpose for maintaining these physical activity records was to assist the investigators in determining the accuracy of the Tegner and Lysholm Activity Scale scores. Each subject was required to complete 12 weeks of the assigned exercise protocol.

Methods

Exercise Protocols

Appendix C contains the details and the progression of the exercises prescribed to each experimental group. Compliance was monitored directly through supervision and indirectly through data sheets.

The exercises assigned to Group Two (PT Group) can be divided into two types:

1. Balance
2. Coordination

Balance is the bodily equilibrium or the ability to maintain the center of body mass over the base of support without falling.⁴⁸ Coordination can be defined as highly skilled multimuscular automaticity.¹³⁶ Balance and coordination are closely interrelated as balance can be defined in the following three ways⁴⁸:

1. The ability to maintain a position.
2. The ability to voluntarily move.
3. The ability to react to a perturbation.

Throughout the 12 weeks of proprioceptive training, the maintenance of proper alignment of the lower extremities was emphasized during all exercises. In the first 6 weeks symmetry and precision of movements were emphasized. In the latter 6 weeks, speed was gradually introduced and integrated into the exercise program.

Measures

The following descriptive information was assessed when subjects entered the study:

- a) Age in years.
- b) Weight in kilograms.
- c) Height in centimeters.
- d) Activity level prior to ACL injury (using the Tegner and Lysholm Activity Scale).
- e) Time interval from surgery to entering into the study in months.
- f) Time interval from initial injury to surgery in months.

The outcome measures of this study were:

1. Subjective scores:
 - a) Lysholm and Gillquist Knee Scoring Scale
 - b) Tegner and Lysholm Activity Scale
2. Performance on the one-legged single hop for distance (SLHD) and the one-legged timed hop.
3. Peak torque times for each hamstring muscle.
4. Isokinetic average eccentric and concentric torques of the hamstring and quadriceps muscles.

Study Design

Table 6.1A and 6.1B demonstrate the study design used for this study.

Table 6.1A Study Design

Group	Test Occasions For Measures	
	Occasion One: Within 7 days prior to the start of the 12 weeks.	Occasion Two: Within 7 days after the completion of the 12 weeks.
One (Strength Training)	Measures: Subjective Scores Isokinetic Strength Functional Hop Tests Descriptive Information	Measures: Subjective Score Isokinetic Strength Functional Hop Tests
Two (Proprioceptive Training)	Measures: Subjective Scores Isokinetic Strength Functional Hop Tests Descriptive Information	Measures: Subjective Scores Isokinetic Strength Functional Hop Tests

Table 6.1B: Study Design

Group	Test Occasions for Measure		
	Occasion One: Within 7 days prior to the start of the 12 weeks.	Occasion Two: In the 6 th week of the 12 weeks.	Occasion Three: Within 7 days after the completion of the 12 weeks.
One (Strength Training)	Measure: Peak Torque Time	Measure: Peak Torque Time	Measure: Peak Torque Time
Two (Proprioceptive Training)	Measure: Peak Torque Time	Measure: Peak Torque Time	Measure: Peak Torque Time

Subjective Scores

The modified Lysholm and Gillquist Knee Scoring Scale and the Tegner and Lysholm Activity Scale were the two subjective scoring scales used in this study.¹³⁰ The purpose of administering the modified Lysholm and Gillquist Knee Scoring Scale and the Tegner and Lysholm Activity Scale is to detect any changes in the subjects' level of activity and function before and after 12 weeks of intervention. Examples of the above subjective scoring scales are included in Appendix B.

Function Hop Tests

The one-legged single hop for distance (SLHD) and the one-legged timed hop were conducted in the manner described by Booher et al.¹²⁹. For the one-legged single hop for distance test, a 4 meter measuring tape that was marked in centimeters (and inches) was secured to the floor. Two practice trials, each separated by 30 seconds, were performed by each subject prior to actual testing. A period of 60 seconds was given after subjects completed their practice trials. Subjects were instructed to stand on one leg and to hop as far as possible, landing on the same limb. Subjects were positioned with their toes touching the zero mark. The distance from the zero mark to their heels was measured and recorded. Each limb was tested twice. A 30 second period was given after subjects completed each test trial. The ACL intact limb was always tested first. The mean of the two trials for each limb was calculated and used as the criterion score.

For the one-legged timed hop test, a distance of six meters was measured. Two practice trials, each separated by 30 seconds, were performed prior to actual testing. A period of 60 seconds was given after subjects completed their practice trials. Subjects were encouraged to use large one-legged hopping motions to perform a series of hops over the total distance. Subjects were positioned with their toes touching the zero mark. Timing of the test began when the subjects sprang forward and ended when they crossed over the finish mark. Time was recorded by the investigator to the nearest 1/100 second. Each limb was tested twice. A 30 second period was given after subjects completed each test trial. The ACL intact limb was always tested first. The mean of the two trials was calculated and used as the criterion score.

Peak Hamstring Torque Time

Peak torque times of the hamstring muscles were measured according to the procedure described in the pilot study of the second test occasion. The only change made to that described in the pilot study was the length of the force arm, which was positioned such that it was no longer than 70% of the length of the lower leg (or of the tibia). The ACL intact limb was always tested first. Test results were saved as ASCII files and transferred onto 3.5" computer discs. The ASCII files recorded the factor of "time" in 0.01 second or 10 millisecond intervals. The slowest and the fastest times to hamstring peak torque were eliminated from the six trials performed by each limb of the subjects. The mean of the remaining four trials was used as the criterion score.

Unlike the other measures used in this study, PTT was measured on 3 separate test occasions. PTT was measured prior to the start of the prescribed exercise program, at 6 weeks into the program, and upon the completion of the program. Peak hamstring torque times were assessed after muscle torque testing was completed for the tested leg at test occasions one and three. There was a 5 minute rest interval between the completion of muscle torque testing and the assessment of PTT.

Muscle Torque (Strength)

Muscle torque was measured using the KIN-COM. The KIN-COM has been shown to be a reliable and valid machine for testing and training.¹¹⁴ Quadriceps and hamstring (concentric and eccentric) muscle torques were assessed bilaterally at 45 degrees per second. The following test protocols were performed (in order):

1. ACL intact Quadriceps at 45°/second.
2. ACL intact Hamstring at 45°/second.
3. ACL reconstructed Quadriceps at 45°/second.
4. ACL reconstructed Hamstring at 45°/second.

All tests for measuring quadriceps muscle torque were performed between 10 and 90 degrees of knee flexion. To protect the ACL graft, the last 10 degrees of knee extension was eliminated during quadriceps muscle torque testing. All tests for measuring hamstring muscle torque were performed between 0 and 90 degrees of knee flexion.

Gravity compensation was performed for all isokinetic strength testing. A low acceleration rate was used for all tests.

Prior to testing, all subjects completed 10 minutes of stationary cycling followed by three repetitions of static quadriceps and hamstring stretching, holding each repetition for 20 seconds. This was to ensure the subjects did not develop muscle cramping while being tested on the KIN-COM. All subjects were also given verbal instructions regarding the test protocol and the use of the KIN-COM dynamometer.

Once the subject was familiar with the procedure, he/she was seated on the KIN-COM with their pelvis and tested thigh secured to the bench. The subject's trunk was also comfortable, but firmly, strapped to the back of the KIN-COM bench seat. The axis of motion of the KIN-COM was aligned with the lateral femoral condyle of the tested knee. The dynamometer lever arm was approximately 70% of the length measured from the lateral knee joint line to the distal portion of the medial malleolus.

Once positioned, subjects were given a practice session for each muscle tested. Practice sessions consisted of five repetitions, three of which were performed submaximally followed by two which were performed with maximum effort. After a 2 minute rest interval, subjects were asked to perform repetitions with maximal effort until three torque curves that overlapped each other were produced on the KIN-COM screen. There was a 10 second intercontraction pause between each concentric and eccentric phase. Test results were saved onto 3.5" computer discs.

Surgical Procedure

The surgical technique used to reconstruct the injured anterior cruciate ligaments is similar to that described by Gomez et al.¹³⁵. In this technique, the ipsilateral semitendinosus tendon is dissected proximally, but left undisturbed distally. A 6 mm drill hole is placed through the proximal tibia, exiting at the attachment of the ACL. This drill hole is positioned so that the remnants of the original ACL will surround it. A lateral incision 4 cm long is made at the flare of the lateral femoral epicondyle. The iliotibial band is incised and dissection is made into the popliteal space to expose the site of exit of the semitendinosus tendon from the joint through the posterior capsule. The semitendinosus graft is threaded through the drill hole and the remaining stump of the

ACL. The resulting ligament/tendon complex is then passed through the posterior capsule of the knee and attached to the lateral intramuscular septum in the over the top fashion. The tendon is fixed to roughened bone just inferior to the attachment of the lateral intermuscular septum, and the stump of the ACL is sutured to the adjacent periosteum. This technique attempts to preserve mechanoreceptors in this area, which would otherwise be removed with other surgical techniques.

Statistics

Statistical analysis began with an one-way analysis of variance to determine if there were any significant differences between the two groups on any of the descriptive and outcome measures assessed at test occasion one.

Repeated-measures analysis of variance was the chosen statistical tool to determine if there were any significant differences at the end of the 12 weeks between Group One and Group Two for each of the four outcome measures used in this research study.

Correlation Analyses

Pearson product-moment correlation coefficients were calculated to determine which of the following variables significantly correlated with the two functional hop tests (performances measured at test occasion two):

1. Average concentric quadriceps torque (measured at the test occasion two).
2. Average eccentric quadriceps torque (measured at test occasion two).
3. Average concentric hamstring torque (measured at test occasion two).
4. Average eccentric hamstring torque (measured at test occasion two).
5. PTT of the hamstring muscle (measured at test occasion three)

Those variables which significantly correlated with the two functional hop tests were used for subsequent regressional analyses

The level of significance for all statistical tests were set at $p \leq 0.05$.

Chapter Seven RESULTS

Descriptive Data of Subjects

Table 7.1 provides a description of the 10 subjects involved in this study.

Table 7.1: Descriptive Data of Subjects

Variable	Group	Mean	Std. Deviation	95% Confidence Interval for Mean		Minimum	Maximum
				Lower Bound	Upper Bound		
Height	One	175.10	10.64	161.88	188.32	165.70	190.80
(cm)	Two	168.14	10.34	155.30	180.98	158.10	179.70
Weight	One	93.30	35.18	49.62	136.98	61.50	150.00
(kg)	Two	67.10	13.96	49.77	84.43	52.00	90.00
Age	One	24.66	2.66	21.35	27.97	22.50	29.30
(year)	Two	25.04	3.68	20.47	29.61	20.40	30.50
Activity Level Prior To Injury	One	8.60	1.14	7.18	10.02	7.00	10.00
(Tegner)	Two	8.80	1.10	7.44	10.16	7.00	10.00
Time From Surgery To Study	One	12.20	8.34	1.84	22.56	7.00	27.00
(month)	Two	6.70	0.84	5.66	7.74	6.00	8.00
Time From Injury To Surgery	One	23.75	26.84	-9.57	57.08	2.00	55.00
(month)	Two	29.00	57.62	-42.55	100.55	1.00	132.00

All subjects were right dominant. In Group One, 3 subjects had their right ACL reconstructed and 2 subjects had their left ACL reconstructed. In Group Two, 3 subjects had their right ACL reconstructed and 2 subjects had their left ACL reconstructed. Group One consisted of 3 males and 2 females. Group Two consisted of 1 male and 4 females.

An one-way analysis of variance demonstrated no significant differences between the two groups in any of the descriptive data collected at test occasion one.

Table 7.2: Descriptive Data of Subjects (One-Way ANOVA)

Variable		Sum of Squares	df	Mean Square	F	Sig.
Height (cm)	Between Groups	121.10	1	121.10	1.10	.325
	Within Groups	881.27	8	110.16		
Weight (kg)	Between Groups	1716.10	1	1716.10	2.40	.160
	Within Groups	5730.00	8	716.25		
Age (year)	Between Groups	0.361	1	0.361	.04	.856
	Within Groups	82.66	8	10.33		
Activity Level Prior To	Between Groups	0.10	1	0.100	.08	.784
Injury (Tegner)	Within Groups	10.00	8	1.25		
Time From Surgery To	Between Groups	75.62	1	75.62	2.15	.181
Study (month)	Within Groups	281.10	8	35.14		
Time From Injury To	Between Groups	68.91	1	68.91	.03	.858
Surgery (month)	Within Groups	16163.88	8	2020.48		

In the one-way analysis of variance conducted to determine if the two groups were different in any of the four outcome measures assessed at test occasion one, a significant difference in average concentric and eccentric torque of the quadriceps muscle of the ACL reconstructed limb was found between the two groups. There are two possibilities for these differences:

1. There are more males in Group One (ST Group) than in Group Two (PT Group). Thus, the significantly greater quadriceps strength (of the ACL reconstructed limb) demonstrated by the strength training group at test occasion one may be secondary to the different female to male ratios between the two groups.
2. Although the time interval from surgery to entering the study was found to be not significantly different between the two groups, the mean time interval for Group One was greater than Group Two. Thus, it is possible that subjects in the strength training group recovered a greater percentage of their pre-injury quadriceps strength than those in the proprioceptive training group.

Table 7.3: Measures at Test Occasion One (One-Way ANOVA)

Torque (Nm)		Sum of Squares	df	Mean Square	F	Sig.
Average Concentric Torque of Quadriceps	Between Groups	10304.00	1	10304.10	10.00	.013
	Within Groups	8242.00	8	1030.25		
Average Eccentric Torque of Quadriceps	Between Groups	16564.90	1	16564.90	14.40	.005
	Within Groups	9205.20	8	1150.65		

Subjects in the strength training group completed a mean of 31.6 ± 3.44 sessions while subjects in the proprioceptive training group completed a mean of 31.4 ± 1.82 sessions of the total 36 sessions.

Subjective Results

Lysholm and Gillquist Knee Scoring Scale

The following tables provide a description of Lysholm and Gillquist scores obtained from the subjects in Group One and Group Two before and after the prescribed training protocols.

Table 7.4: Lysholm and Gillquist Knee Scoring Scale Results

Group One (n=5) Strength Training				Group Two (n=5) Proprioceptive Training			
Subject	Pre	Post	Change	Subject	Pre	Post	Change
1	95	100	5	1	91	95	4
2	99	100	1	2	75	86	11
3	95	100	5	3	93	95	2
4	91	96	5	4	88	85	-3
5	83	88	5	5	91	100	9

Table 7.5: Descriptive Data for Lysholm and Gillquist Knee Scoring Scale Scores

		Mean	Std. Deviation	95% Confidence Interval	
Group	Occasion			Lower Bound	Upper Bound
One	1	92.60	6.07	85.70	99.50
(ST)	2	96.80	5.22	90.74	102.85
Two	1	87.60	7.27	80.70	94.50
(PT)	2	92.20	6.46	86.15	98.25

There was a significant difference in the scores between test occasions. There was no significant difference between groups nor was there a group by test occasion interaction effect on the Lysholm and Gillquist scores. An interaction effect is the combined effect of two or more independent variables (i.e. group and test occasion) on a dependent variable (i.e. Lysholm and Gillquist score).¹³⁴

Table 7.6: Lysholm and Gillquist Knee Scoring Scale
Tests of Within-Subjects Effects (RM ANOVA)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Test Occasion	96.80	1	96.80	11.22	.010
Occasion * Group	0.20	1	0.20	0.02	.883
Error (Occasion)	69.00	8	8.62		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	115.20	1	115.20	1.63	.237
Error	565.00	8	70.62

Figure 7.1

Lysholm and Gillquist Knee Scoring Scale Scores Pre and Post Intervention vs. Group

Figure 7.1 is a boxplot. Boxplots give an overview of within group distributions.¹³⁴ The horizontal line in the middle of the boxes marks the median (score) of the sample. The edges (or the hinges) of each box mark the 25th (bottom hinge) and the 75th (top hinge) percentiles. Thus, the central 50 percent of the data values fall within the range of the box. The length of the box (the difference between the values of the hinges) is called the hspread. The vertical lines extending up and down from each box (whiskers) show the range of values that fall within 1.5 hspreads of the hinges. Boxplots are also very useful in demonstrating any outliers or extremes within the distributions. Outliers are numeric values that does not fall within the range of most scores in a distribution. Extremes are similar to outliers, but more deviant (than outliers) from the distribution. Outliers and extremes can distort statistical associations or correlations.¹³⁴

Due to the number of subjects used in this study, the presence of outliers and extremes were common. However, unless these outliers or extremes demonstrated a trend that was opposite of the general distribution, they will not be discussed in detail.

Figure 7.1 indicates subject 5 of Group One was an outlier while subject 2 of Group Two was an extreme at test occasion one. Both subjects possessed Lysholm and Gillquist scores that were lower than the general distribution. However, at the end of the 12 weeks, subject 2 of Group Two was no longer an extreme while subject 5 of Group One remained an outlier.

Figure 7.2
Scatter Plot of Lysholm and Gillquist Scores
(Linear Regressional Lines)

Figure 7.2 is a scatter plot with linear regressional lines. Scatter plots are useful in graphic representations of the relationship between two variables (i.e. group and test occasion). Figure 7.2 demonstrates the lack of a group by test occasion interaction effect on Lysholm and Gillquist scores. It is clear from Figure 7.2 that both experimental groups made similar gains in Lysholm and Gillquist scores after 12 weeks of training.

Tegner and Lysholm Activity Scale

The following tables provides a description of the subjective scores obtained from using the Tegner and Lysholm Activity Scale from the subjects in Group One and Group Two before and after the prescribed training protocols.

Table 7.7: Tegner and Lysholm Activity Scale Results

Group One (n=5) Strength Training				Group Two (n=5) Proprioceptive Training			
Subject	Pre	Post	Change	Subject	Pre	Post	Change
1	7	8	1	1	6	6	0
2	8	8	0	2	5	7	2
3	4	7	3	3	3	6	3
4	4	6	2	4	4	6	2
5	6	7	1	5	5	9	4

Table 7.8: Descriptive Data For Tegner and Lysholm Activity Scale Scores

		Mean	Std. Deviation	95% Confidence Interval	
Group	Occasion			Lower Bound	Upper Bound
One	1	5.80	1.79	4.25	7.35
	2	7.20	0.84	6.07	8.33
Two	1	4.60	1.14	3.05	6.15
	2	6.80	1.30	5.67	7.93

A significant difference in Tegner and Lysholm scores was found between test occasions. There was no significant difference between groups nor was there a group by test occasion interaction effect on Tegner and Lysholm scores.

Table 7.9: Tegner and Lysholm Activity Scale
Tests of Within-Subjects Effects (RM ANOVA)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Test Occasion	16.20	1	16.20	18.51	.003
Occasion * Group	0.80	1	0.80	0.91	.367
Error (Occasion)	7.00	8	0.88		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	3.20	1	3.20	1.24	.297
Error	20.60	8	2.58

Figure 7.3

Tegner and Lysholm Activity Scale Scores Pre and Post Intervention vs. Group

Figure 7.3 indicates that subject 5 of Group Two was an outlier after 12 weeks of proprioceptive training. This subject's Tegner and Lysholm Activity score was higher than the general distribution of Group Two at the end of the 12 weeks. There were no outliers or extremes in Group One.

Figure 7.4
Scatter Plot of Tegner and Lysholm Scores
(Linear Regression Lines)

Figure 7.4 indicates the lack of a group by test occasion interaction effect on the Tegner and Lysholm scores. Although subjects in Group Two appeared to demonstrate greater improvements than those in Group One after 12 weeks of training, it was not statistically significant. Thus, both experimental groups made similar gains in Tegner and Lysholm scores after 12 weeks of training.

Objective Results

Isokinetic Torque (Strength)

Isokinetic values used for statistical analyses were average torques generated at 45°/second. Absolute torque values were used for statistical analyses rather than symmetry indexes. Symmetry indexes (i.e. dividing the ACL reconstructed knee average torque by the ACL intact knee average torque and multiplying the quotient by 100) were not used for statistical analyses because the reliability coefficients (ICC) observed for absolute torques were higher than those observed for ratios or symmetry indexes (Appendix D). Ratio data are particularly appealing clinically because scores may be standardized and the subject may act as his or her own control.¹²¹ Although ratios are frequently used to describe the extent of abnormality, the reliability of ratio data may be questionable. Because the ratio is the quotient of two absolute numbers, each of which may vary in two directions upon repeat testing, the reliability of ratio data may be less than that associated with the absolute scores used to calculate the ratio.¹²¹

Table 7.10: Descriptive Data for Average Torques (Nm) at Test Occasion One

Average Torque (Nm) Measured at 45°/second	Group One ($\bar{x} \pm SD$)	Group Two ($\bar{x} \pm SD$)	Total ($\bar{x} \pm SD$)
Concentric Quadriceps (Nm)	n = 5	n = 5	N = 10
ACL Reconstructed	144.40 $\pm$ 31.42	80.20 $\pm$ 32.76	112.30 $\pm$ 45.39
ACL Intact	149.40 $\pm$ 40.30	116.80 $\pm$ 30.23	133.10 $\pm$ 37.72
Eccentric Quadriceps (Nm)	n = 5	n = 5	N = 10
ACL Reconstructed	161.00 $\pm$ 38.25	79.60 $\pm$ 28.95	120.30 $\pm$ 53.51
ACL Intact	172.60 $\pm$ 59.23	142.00 $\pm$ 43.14	157.30 $\pm$ 51.44
Concentric Hamstring (Nm)	n = 5	n = 5	N = 10
ACL Reconstructed	71.00 $\pm$ 24.63	53.20 $\pm$ 15.53	62.10 $\pm$ 21.56
ACL Intact	80.80 $\pm$ 26.58	61.00 $\pm$ 23.95	70.90 $\pm$ 26.04
Eccentric Hamstring (Nm)	n = 5	n = 5	N = 10
ACL Reconstructed	85.40 $\pm$ 28.35	58.60 $\pm$ 17.16	72.00 $\pm$ 26.22
ACL Intact	93.80 $\pm$ 37.62	78.00 $\pm$ 26.62	85.90 $\pm$ 31.83

Table 7.11: Descriptive Data for Average Torques (Nm) at Test Occasion Two

Average Torque (Nm) Measured at 45°/second	Group One ($\bar{x} \pm SD$)	Group Two ($\bar{x} \pm SD$)	Total ($\bar{x} \pm SD$)
Concentric Quadriceps (Nm)	n = 5	n = 5	N = 10
ACL Reconstructed	142.80 $\pm$ 40.91	104.20 $\pm$ 34.66	123.50 $\pm$ 41.13
ACL Intact	154.80 $\pm$ 36.81	132.60 $\pm$ 31.20	143.70 $\pm$ 34.23
Eccentric Quadriceps (Nm)	n = 5	n = 5	N = 10
ACL Reconstructed	164.00 $\pm$ 46.67	116.80 $\pm$ 37.92	140.40 $\pm$ 47.18
ACL Intact	175.40 $\pm$ 37.18	150.40 $\pm$ 34.36	162.90 $\pm$ 36.23
Concentric Hamstring (Nm)	n = 5	n = 5	N = 10
ACL Reconstructed	73.00 $\pm$ 16.93	61.20 $\pm$ 19.72	67.10 $\pm$ 18.41
ACL Intact	79.20 $\pm$ 24.61	65.40 $\pm$ 23.42	72.30 $\pm$ 23.79
Eccentric Hamstring (Nm)	n = 5	n = 5	N = 10
ACL Reconstructed	85.40 $\pm$ 23.74	71.60 $\pm$ 17.17	78.50 $\pm$ 20.84
ACL Intact	99.40 $\pm$ 32.89	85.00 $\pm$ 22.44	92.20 $\pm$ 27.61

Average Concentric Quadriceps Torque of the ACL Reconstructed Limb

There was a significant difference between Group One and Group Two in the average concentric quadriceps torque of the ACL reconstructed limb. Also, there was a significant difference between the two test occasions and a significant group by test occasion interaction effect on the average concentric quadriceps torque.

Table 7.12: Average Concentric Quadriceps Torque of the ACL Reconstructed Limb
Tests of Within-Subjects Effects (RM ANOVA)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Test Occasion	627.20	1	627.20	7.71	.024
Occasion * Group	819.20	1	819.20	10.073	.013
Error (Occasion)	650.60	8	81.32		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	13209.80	1	13209.80	5.54	.046
Error	19091.00	8	2386.38

Figure 7.5
Average Concentric Quadriceps Torque of the ACL Reconstructed Limb Pre and Post Intervention vs. Group

Figure 7.5 indicates that subject 3 of Group Two was an outlier after 12 weeks of proprioceptive training. The subject obtained an average concentric quadriceps torque of the ACL reconstructed limb that was higher than the general distribution at the end of the 12 weeks. There was no outliers or extremes in Group One.

Figure 7.6
Scatter Plot of Average Concentric Quadriceps Torque of the ACL Reconstructed Limb
(Linear Regressional Lines)

Figure 7.6 demonstrates an group by test occasion interaction effect on the average concentric quadriceps torque of the ACL reconstructed limb. It is clear from Figure 7.6 that Group Two made greater gains in average concentric quadriceps torque of the ACL reconstructed knee than Group One after 12 weeks of training.

Average Concentric Quadriceps Torque of the ACL Limb

There was no significant difference between Group One and Two in the average concentric quadriceps torque of the ACL intact limb, nor was there a significant group by test occasion interaction effect. There was, however, a significant difference in the average concentric quadriceps torque between test occasions.

Table 7.13: Average Concentric Quadriceps Torque of the ACL Intact Limb
Tests of Within-Subjects Effects (RM ANOVA)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Test Occasion	561.80	1	561.80	9.15	.016
Occasion * Group	135.20	1	135.20	2.20	.176
Error (Occasion)	491.00	8	61.38		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	3753.800	1	3753.800	1.583	.244
Error	18971.000	8	2371.375

Figure 7.7
Average Concentric Quadriceps Torque of the ACL Intact Limb Pre and Post Intervention vs. Group

Figure 7.7 indicates that subject 3 of Group Two was an outlier at test occasion two. The subject obtained an average concentric quadriceps torque of the ACL intact limb that was higher than the general distribution of Group Two after 12 weeks of training. There was no outliers or extremes in Group One.

Figure 7.8
Scatter Plot of Average Concentric Quadriceps Torque of the ACL Intact Limb
(Linear Regressional Lines)

Figure 7.8 indicates the lack of a group by test occasion interaction effect on the average concentric quadriceps torque of the ACL intact limb. It is clear from Figure 7.8 that both experimental groups made similar gains in the average concentric quadriceps torque of the ACL intact limb after 12 weeks of training.

Average Eccentric Quadriceps Torque of the ACL Reconstructed Limb

There was a significant difference between Group One and Group Two in the average eccentric quadriceps torque of the ACL reconstructed limb. Also, there was a significant difference between the two test occasions and a significant group by test occasion interaction effect on the average eccentric quadriceps torque of the ACL reconstructed limb.

Table 7.14: Average Eccentric Quadriceps Torque of the ACL Reconstructed Limb
Tests of Within-Subjects Effects (RM ANOVA)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Test Occasion	2020.05	1	2020.05	8.03	.022
Occasion * Group	1462.05	1	1462.05	5.81	.042
Error (Occasion)	2012.40	8	251.55		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	20672.45	1	20672.45	7.64	.025
Error	21659.60	8	2707.45

Figure 7.9
Average Eccentric Quadriceps Torque of the ACL Reconstructed Limb Pre and Post
Intervention vs. Group

Figure 7.9 indicates that subject 2 of Group Two was an outlier at test occasion one. This subject had an average eccentric quadriceps torque of the ACL reconstructed limb that was lower than the general distribution of Group Two at test occasion one. However, the subjects was no longer an outlier by test occasion two. There were no outliers or extremes in Group One.

Figure 7.10
Scatter Plot of Average Eccentric Quadriceps Torque of the ACL Reconstructed Limb
(Linear Regressional Lines)

Figure 7.10 demonstrates a group by test occasion interaction effect on the average eccentric quadriceps torque of the ACL reconstructed limb. It is clear from Figure 7.10 that Group Two made greater gains in average eccentric quadriceps torque of the ACL reconstructed limb than Group One after 12 weeks of training.

Average Eccentric Quadriceps Torque of the ACL Intact Limb

There was no significant difference between Group One and Group Two in the average eccentric quadriceps torque of the ACL intact limb. Also, there was no significant difference between the test occasions and no significant group by test occasion interaction effect on the average eccentric quadriceps torque of the ACL intact limb.

Table 7.15: Average Eccentric Quadriceps Torque of the ACL Intact Limb
Tests of Within-Subjects Effects (RM ANOVA)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Test Occasion	156.80	1	156.80	.43	.529
Occasion * Group	39.20	1	39.20	.11	.751
Error (Occasion)	2903.00	8	362.88		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	3864.20	1	3864.20	1.07	.331
Error	28824.60	8	3603.08		

Average Concentric Hamstring Torque of the ACL Reconstructed Limb

There was no significant difference between Group One and Group Two in the average concentric hamstring torque of the ACL reconstructed knee. Also, there was no significant difference between the two test occasions and no significant group by test occasion interaction effect on the average eccentric hamstring torque of the ACL reconstructed limb.

Table 7.16: Average Concentric Hamstring Torque of the ACL Reconstructed Limb
Tests of Within-Subjects Effects (RM ANOVA)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Test Occasion	125.00	1	125.00	2.46	.156
Occasion * Group	45.00	1	45.00	.88	.374
Error (Occasion)	407.00	8	50.88		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	1095.20	1	1095.20	1.54	.250
Error	5684.60	8	710.58

Figure 7.11
Average Concentric Hamstring Torque of the ACL Reconstructed Limb Pre and Post Intervention vs. Group

Figure 7.11 indicates that subject 3 of Group Two was an extreme score at test occasion two. This subject obtained an average concentric hamstring torque of the ACL reconstructed knee that was higher than the general distribution of Group Two after 12 weeks of training. There were no outliers or extremes in Group One.

Average Concentric Hamstring Torque of the ACL Intact Limb

There was no significant difference between Group One and Group Two in the average concentric hamstring torque of the ACL intact limb. Also, there was no significant difference between the test occasions and no significant group by test occasion interaction effect on average concentric hamstring torque of the ACL intact limb

Table 7.17: Average Concentric Hamstring Torque of the ACL Intact Limb
Tests of Within-Subjects Effects (RM ANOVA)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Test Occasion	9.80	1	9.800	.39	.550
Occasion * Group	45.00	1	45.000	1.79	.218
Error (Occasion)	201.20	8	25.150		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	1411.20	1	1411.20	1.18	.308
Error	9535.60	8	1191.95		

Average Eccentric Hamstring Torque of the ACL Reconstructed Limb

There was no significant difference between Group One and Group Two in the average eccentric hamstring torque of the ACL reconstructed limb. However, there was a significant difference between the test occasions and a significant group by test occasion interaction effect on the average eccentric hamstring torque of the ACL reconstructed limb.

Table 7.18: Average Eccentric Hamstring Torque of the ACL Reconstructed Limb
Tests of Within-Subjects Effects (RM ANOVA)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Test Occasion	211.25	1	211.25	5.50	.047
Occasion * Group	211.25	1	211.25	5.50	.047
Error (Occasion)	307.00	8	38.38		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	2060.45	1	2060.45	2.19	.177
Error	7519.80	8	939.98

Figure 7.12
Average Eccentric Hamstring Torque of the ACL Reconstructed Limb Pre and Post
Intervention vs. Group

There were no outliers or extremes for either experimental group.

Figure 7.13

Scatter Plot of Average Eccentric Hamstring Torque of the ACL Reconstructed Limb (Linear Regressional Lines)

Figure 7.13 demonstrates a group by test occasion interaction effect on average eccentric hamstring torque of the ACL reconstructed limb. It is clear from Figure 7.13 that Group Two made greater gains in average eccentric hamstring torque of the ACL reconstructed limb than Group One after 12 weeks of training.

Average Eccentric Hamstring Torque of the ACL Intact Limb

There was no significant difference between Group One and Group Two in the average eccentric hamstring torque of the ACL intact limb, nor was there a group by test occasion interaction effect. There was, however, a significant difference in average eccentric hamstring torque of the ACL intact limb between test occasions.

Table 7.19: Average Eccentric Hamstring Torque of the ACL Intact Limb Tests of Within-Subjects Effects (RM ANOVA)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Test Occasion	198.45	1	198.45	7.30	.027
Occasion * Group	2.45	1	2.45	.09	.772
Error (Occasion)	217.60	8	27.20		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	1140.05	1	1140.05	.62	.452
Error	14620.40	8	1827.55

Figure 7.14

Average Eccentric Hamstring Torque of the ACL Intact Limb Pre and Post Intervention vs. Group

Figure 7.14 indicates subject 3 of Group Two as an outlier at test occasion one and an extreme score at test occasion two. This indicates that subject 3 had a average eccentric hamstring torque of the ACL intact knee that was higher than the general distribution of Group Two at both test occasions. Subject 4 of Group Two was an extreme (lower) score at test occasion two.

Figure 7.15
Scatter Plot of Average Eccentric Hamstring Torque of the ACL Intact Limb
(Linear Regressional Lines)

Figure 7.15 demonstrates the lack of a group by test occasion interaction effect on the average eccentric hamstring torque of the ACL intact knee. It is clear from Figure 7.15 that both experimental groups made similar gains in average eccentric hamstring torque of the ACL intact knee after 12 weeks of training.

Functional Hop Tests

Symmetry indexes were not used for statistical analyses of functional hop tests because the reliability coefficients (ICC) observed for absolute values were higher than those for ratios or symmetry indexes (Appendix D). Therefore, absolute values were used for statistical analyses.

Table 7.20: Descriptive Data for Functional Hop Tests at Test Occasion One

Functional Hop Test	Group One ($\bar{x} \pm SD$)	Group Two ($\bar{x} \pm SD$)	Total ($\bar{x} \pm SD$)
Timed Hop (sec)	n = 5	n = 5	N = 10
ACL Reconstructed	2.34 $\pm$ 0.22	2.75 $\pm$ 0.58	2.54 $\pm$ 0.47
ACL Intact	2.27 $\pm$ 0.25	2.21 $\pm$ 0.20	2.24 $\pm$ 0.22
Single Hop For Distance (cm)	n = 5	n = 5	N = 10
ACL Reconstructed	160.34 $\pm$ 33.76	133.30 $\pm$ 38.32	146.82 $\pm$ 38.32
ACL Intact	168.20 $\pm$ 29.94	165.61 $\pm$ 24.02	166.90 $\pm$ 25.63

Table 7.21: Descriptive Data for Functional Hop Test at Test Occasion Two

Functional Hop Test	Group One ($\bar{x} \pm SD$)	Group Two ($\bar{x} \pm SD$)	Total ($\bar{x} \pm SD$)
Timed Hop (sec)	n = 5	n = 5	N = 10
ACL Reconstructed	1.82 $\pm$ 0.25	2.03 $\pm$ 0.23	1.92 $\pm$ 0.25
Normal	1.74 $\pm$ 0.26	1.84 $\pm$ 0.15	1.79 $\pm$ 0.21
Single Hop for Distance (cm)	n = 5	n = 5	N = 10
ACL Reconstructed	181.04 $\pm$ 32.57	150.95 $\pm$ 35.90	166.00 $\pm$ 36.00
ACL Intact	179.25 $\pm$ 23.76	171.34 $\pm$ 29.10	175.24 $\pm$ 25.37

One-Legged Timed Hop Performance of the ACL Reconstructed Limb

There was no significant difference between Group One and Group Two in the performance of the one-legged timed hop, nor was there a significant group by test occasion interaction effect. There was, however, a significant difference in the performance of the one-legged timed hop between test occasions.

Table 7.22: One-Legged Time Hop Performance of the ACL Reconstructed Limb Tests of Within-Subjects Effects (RM ANOVA)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Test Occasion	1.925	1	1.925	30.694	.001
Occasion * Group	4.851E-02	1	4.851E-02	.773	.405
Error (Occasion)	0.502	8	6.272E-02		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	.476	1	0.476	2.524	.151
Error	1.508	8	0.189

Figure 7.16
One-Legged Timed Hop Performance of the ACL Reconstructed Limb Pre and Post Intervention vs. Group

Figure 7.16 indicates subject 2 of Group Two was an outlier at both test occasions. This subject's performance on the one-legged timed hop was worse than the general distribution of performances for Group Two. Subject 5 of Group Two was also an outlier, but only at test occasion two. This subject's performance on the one-legged timed hop was better than the general distribution.

Subject 5 of Group One was an outlier at test occasion one. The subject's performance on the one-legged timed hop was better than the general distribution of Group One at test occasion one.

Figure 7.17

Scatter Plot of One-Legged Timed Hop Performance of the ACL Reconstructed Limb
(Linear Regressional Lines)

Figure 7.17 demonstrates the lack of a group by test occasion interaction effect on the one-legged timed hop performance of the ACL reconstructed limb. It is clear from Figure 7.17 that both groups made very similar improvements in the performance of the one-legged timed hop.

One-Legged Timed Hop Performance of the ACL Intact Limb

There was no significant difference between Group One and Group Two in the one-legged timed hop performance of the ACL intact limb, nor was there a significant group by test occasion interaction effect. There was, however, a significant difference in the one-legged timed hop performance of the ACL intact limb between test occasions

Table 7.23: One-Legged Timed Hop Performance of the ACL Intact Limb
Tests of Within-Subjects Effects (RM ANOVA)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Test Occasion	1.01	1	1.01	44.76	.000
Occasion * Group	3.121E-02	1	3.121E-02	1.39	.273
Error (Occasion)	0.18	8	2.252E-02		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	2.205E-03	1	2.205E-03	.029	.868
Error	.600	8	7.504E-02

Figure 7.18
One-Legged Timed Hop Performance of the ACL Intact Limb Pre and Post Intervention
vs. Group

Figure 7.18 indicates subject 3 and 5 of Group Two as extremes scores at test occasion two. The performance of subject 3 on the one-legged time hop was worse than the general distribution of Group Two at test occasion two. The performance of subject 5, however, was better than the general distribution at test occasion two.

Subject 3 of Group One was an outlier at both test occasions. The performance of subject 3 on the one-legged timed hop was slower than the general distribution of Group One.

Figure 7.19
Scatter Plot of One-Legged Timed Hop Performance of the ACL Intact Limb
(Linear Regressional Lines)

Figure 7.19 demonstrates the lack of a group by test occasion interaction effect on the one-legged timed hop performance of the ACL intact limb. Although subjects in Group One demonstrated a greater improvements in their one-legged timed hop performance on the ACL intact knee after the 12 weeks, it was not significant. Thus, both experimental groups made similar improvements in the one-legged timed hop performance of the ACL intact limb after 12 weeks of training.

One-Legged Single Hop for Distance Performance of the ACL Reconstructed Limb

There was no significant difference between Group One and Group Two in the one-legged single hop for distance performance of the ACL reconstructed limb, nor was there a significant group by test occasion effect. There was, however, a significant difference in the performance of the one-legged single hop for distance between test occasions.

Table 7.24: SLHD Performance of the ACL Reconstructed Limb
Tests of Within-Subjects Effects (RM ANOVA)

Test Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Occasion	1838.40	1	1838.40	26.31	.001
Occasion * Group	11.63	1	11.63	0.17	.694
Error (Occasion)	558.94	8	69.87		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	4079.80	1	4079.80	1.61	.240
Error	20232.11	8	2529.01

Figure 7.20

SLHD Performance of the ACL Reconstructed Limb Pre and Post Intervention vs. Group

Figure 7.20 indicates subject 3 of Group Two as an outlier (high score) and subject 2 as an extreme (low score) at test occasion one. However, both subjects were within the general distribution of Group Two at test occasion two. Subject 2 of Group One was an outlier at test occasion two. This subject's performance on the one-legged single hop for distance at test occasion two was better than the general distribution of Group One.

Figure 7.21
Scatter Plot of SLHD Performance of the ACL Reconstructed Limb
(Linear Regressional Lines)

Figure 7.21 demonstrates the lack of a group by test occasion interaction effect on the one-legged single hop for distance performance of the ACL reconstructed knee. It is clear from Figure 7.21 that both experimental groups made very similar improvement in the one-legged single hop for distance performance of the ACL reconstructed limb.

One-Legged Single Hop for Distance Performance for the ACL Intact Limb

There was no significant difference between Group One and Group Two in the one-legged single hop for distance performance of the ACL intact limb, nor was there a significant group by test occasion interaction effect. However, there was a significant difference in the performance of the one-legged single hop for distance between test occasions.

Table 7.25: SLHD Performance of the ACL Intact Limb
Tests of Within-Subjects Effects (RM ANOVA)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Test Occasion	351.961	1	351.961	9.820	.014
Occasion * Group	35.378	1	35.378	.987	.350
Error (Occasion)	286.732	8	35.841		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	137.812	1	137.812	.098	.762
Error	11254.158	8	1406.770

Figure 7.22

SLHD Performance of the ACL Intact Limb Pre and Post Intervention vs. Group

Figure 7.22 indicates subject 2 of Group One as an outlier at test occasion two. This subject performed one-legged single hop for distance performance better than the general distribution of Group One at test occasion two.

Figure 7.23
Scatter Plot of SLHD Performance of the ACL Intact Limb
(Linear Regressional Lines)

Figure 7.23 demonstrates the lack of a group by test occasion interaction effect on the one-legged single hop for distance performance of the ACL intact knee. It is clear from Figure 7.23 that both experimental groups made similar improvements in the one-legged single hop for distance performance of the ACL intact knee.

Peak Torque Time

Table 7.26 contains the descriptive data for peak torque times obtained from the three test occasions.

Table 7.26: Descriptive Data for PTT

PTT (msec)	Group One ($\bar{x} \pm SD$)	Group Two ($\bar{x} \pm SD$)	Total ($\bar{x} \pm SD$)
Occasion One	n = 5	n = 5	N = 10
ACL Reconstructed	482.50 $\pm$ 24.87	478.00 $\pm$ 20.57	480.25 $\pm$ 21.65
ACL Intact	499.00 $\pm$ 32.09	498.00 $\pm$ 34.07	498.50 $\pm$ 31.21
Occasion Two	n = 5	n = 5	N = 10
ACL Reconstructed	498.50 $\pm$ 23.22	456.00 $\pm$ 6.52	477.25 $\pm$ 27.57
ACL Intact	487.00 $\pm$ 35.86	493.50 $\pm$ 33.01	490.25 $\pm$ 32.67
Occasion Three	n = 5	n = 5	N = 10
ACL Reconstructed	480.00 $\pm$ 19.12	472.00 $\pm$ 11.10	476.00 $\pm$ 15.33
ACL Intact	506.00 $\pm$ 28.59	490.00 $\pm$ 29.84	498.00 $\pm$ 28.81

Peak Torque Time for the ACL Reconstructed Limb

There was no significant difference between Group One and Group Two in the peak hamstring torque times, nor was there a difference in PTT between test occasions. There was, however, a significant group by test occasion interaction effect on PTT.

Table 7.27: PTT of the ACL Reconstructed Limb

Tests of Within-Subjects Effects (RM ANOVA)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Test Occasion	95.42	2	47.71	0.23	.798
Occasion * Group	2205.42	2	1102.71	5.29	.017
Error (Occasion)	3332.50	16	208.28		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	2520.83	1	2520.83	3.94	.082
Error	5117.50	8	639.69

Figure 7.24

Peak Torque Time of the ACL Reconstructed Limb Pre and Post Intervention vs. Group

Figure 7.24 indicates subject 4 of Group One as an outlier at test occasion three. This subject had a slower PTT than the general distribution of Group One.

Subjects 3 and 5 of Group Two are indicated by Figure 7.24 as extreme scores at test occasion two. These two subjects were no longer extremes at test occasion three.

Figure 7.25
Scatter Plot of PTT of ACL Reconstructed Limb
(Linear Regressional Lines)

It is evident in Figure 7.25 that the linear regressional lines does not provide an adequate description of the group by test occasion interaction effect on PTT. The scatter plot indicates there may be a curvilinear relationship rather than a linear relationship between the PTT and test occasion.

Figure 7.26
Scatter Plot of PTT of ACL Reconstructed Limb
(Quadratic Regressional Lines)

Figure 7.26 provides a better description of the group by test occasion interaction effect on PTT of the ACL reconstructed limb. It is evident the two experimental groups demonstrated very different trends in PTT within the 12 weeks of training.

Peak Torque Times for the ACL Intact Limb

There was no significant difference between Group One and Group Two for PTT of the ACL intact limb. Also, there was no significant difference in PTT between test occasions and no significant group by test occasion interaction effect.

Table 7.28: PTT of the ACL Intact Limb
Tests of Within-Subjects Effects (RM ANOVA)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Test Occasion	427.92	2	213.96	0.30	.748
Occasion * Group	656.25	2	328.12	0.45	.644
Error (Occasion)	11603.33	16	725.21		

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Group	91.88	1	91.88	0.05	.821
Error	13491.67	8	1686.46		

Results of Regression Analyses

Correlational Analyses

Tables 7.29 and 7.30 summarize the statistically significant results of correlational analyses. There were no significant correlations found between any of the six variables and one-legged timed hop. Four of the six variables were found to have significant correlations with the one-legged single hop for distance.

Table 7.29: Pearson Product-Moment Correlation Coefficients for ACL Intact Limb

SLHD	Coefficient	Significance (two-tailed)
Concentric Quadriceps	0.637	0.033
Eccentric Quadriceps	0.653	0.041
Concentric Hamstring	0.719	0.019
Eccentric Hamstring	0.658	0.038

Table 7.30: Pearson Product-Moment Correlation Coefficients for ACL Reconstructed Limb

SLHD	Coefficient	Significance (two-tailed)
Concentric Quadriceps	0.856	0.002
Eccentric Quadriceps	0.777	0.008
Concentric Hamstring	0.849	0.002
Eccentric Hamstring	0.667	0.035

Regression Analyses

Regression analyses were performed to determine the relative contribution of isokinetic torque (strength) to the performance of one-legged single hop for distance test. Two regression analyses were performed to determine the effects of peak torque time and isokinetic torque on the performance of the two functional hop tests. They were:

1. ACL reconstructed knee (N = 10).
2. ACL intact knee (N = 10).

Regression Analyses for the ACL Reconstructed Limb

The effects of isokinetic torque on functional performance (SLHD) of the ACL reconstructed knee were tested by regression analyses. The following variables had significant effects on functional performance:

1. Average concentric torque of the quadriceps.

Table 7.31: Average Concentric Quadriceps Torque Effect (ACL Reconstructed)

R	R Square	Adjusted R Square	Std. Error of the Estimate
0.856	0.733	0.699	19.7353

Figure 7.27

Average Concentric Quadriceps Torque Effect of the ACL Reconstructed Limb

2. Average eccentric torque of the quadriceps.

Table 7.32: Average Eccentric Quadriceps Torque Effect (ACL Reconstructed)

R	R Square	Adjusted R Square	Std. Error of the Estimate
0.777	0.604	0.554	24.0281

Figure 7.28
Average Eccentric Quadriceps Torque Effect of the ACL Reconstructed Limb

3. Average concentric torque of the hamstring muscle.

Table 7.33: Average Concentric Hamstring Torque Effect (ACL Reconstructed)

R	R Square	Adjusted R Square	Std. Error of the Estimate
0.849	0.720	0.685	20.1942

Figure 7.29
Average Concentric Hamstring Torque Effect of the ACL Reconstructed Limb

4. Average eccentric torque of the hamstring muscle.

Table 7.34: Average Eccentric Hamstring Torque Effect (ACL Reconstructed)

R	R Square	Adjusted R Square	Std. Error of the Estimate
0.667	0.445	0.375	28.4559

Figure 7.30

Average Eccentric Hamstring Torque Effect of the ACL Reconstructed Limb

Regression Analyses for the ACL Intact Limb

The effects of isokinetic torque on functional performance (SLHD) of the ACL intact knee were tested by regression analyses. Analyses found the following variables had significant effects on functional performance:

1. Average concentric torque of the quadriceps muscle

Table 7.35: Average Concentric Quadriceps Torque Effect (ACL Intact)

R	R Square	Adjusted R Square	Std. Error of the Estimate
0.673	0.452	0.384	19.9104

Figure 7.31
Average Concentric Quadriceps Torque Effect of the ACL Intact Limb

2. Average eccentric torque of the quadriceps muscle.

Table 7.36: Average Eccentric Quadriceps Torque (ACL Intact)

R	R Square	Adjusted R Square	Std. Error of the Estimate
0.653	0.427	0.355	20.3743

Figure 7.32
Average Eccentric Quadriceps Torque Effect of the ACL Intact Limb

3. Average concentric torque of the hamstring muscle.

Table 7.37: Average Concentric Quadriceps Torque (ACL Intact)

R	R Square	Adjusted R Square	Std. Error of the Estimate
0.797	0.635	0.590	16.2508

Figure 7.33
Average Concentric Hamstring Torque Effect of ACL Intact Limb

4. Average eccentric torque of the hamstring muscle.

Table 7.38: Average Eccentric Hamstring Torque Effect (ACL Intact)

R	R Square	Adjusted R Square	Std. Error of the Estimate
0.614	0.377	0.299	21.2433

Figure 7.34
Average Eccentric Hamstring Torque Effect of the ACL Intact Limb

Chapter Eight

DISCUSSION

In the last decade, proprioception training has been emphasized in the literature as an important component of rehabilitation programs for individuals with ACL injuries. Numerous studies have documented altered knee proprioception after ACL injuries. However, the effectiveness of proprioceptive training in ACL deficient or ACL reconstructed limbs is not well established in the literature. To the best of the investigators' knowledge, this is the first prospective and randomized study examining the effectiveness of proprioceptive training in individuals with ACL reconstructed knees. Thus, it is difficult to directly compare the results of this study with current findings in the literature. In addition, the method in which PTT was measured in this study has not been used previously as an outcome measure. The method used to measure PTT was duplicated from that described by Small et al.¹, with the exception of the forward angular velocity of the dynamometer lever arm. Thus, the validity of direct comparisons between this study's PTT results and those of the literature may be questionable.

The results of this study indicate that both strength training and proprioception training (of the lower extremities) have an influence on peak hamstring torque time of the ACL reconstructed limb. It is proposed that they influence PTT through different neuromuscular mechanisms. Statistically, this influence was found to be dependent on the interaction of two factors:

1. The type of training.
2. The duration of training.

Peak torque time is a measure of volitional activity of muscle(s) and we propose it relies on the following factors:

1. The sensitivity of the muscle spindles.
2. Kinesthetic awareness of the knee joint.
3. The ability to recruit as many motor units as possible in the shortest amount of time.
4. The coordination of the limb to the specified task.

It is the postulation of this study that there is sensory information originating from the ACL graft and joint afferents that affects the primary spindle afferents via the gamma efferent muscle spindle system. Thus, the ACL graft and joint afferents may contribute to

the continuous preparatory adjustment of muscular stiffness through the gamma efferent muscle spindle system. PTT can be regarded as the ability of the hamstring muscle to increase its stiffness at the time of a displacement (i.e. the forward movement of the dynamometer lever arm). As indicated in the review of the literature, functional joint stability is greatly determined by joint load caused by the contraction (or stiffness) of its surrounding muscles.³⁵ Hence, PTT may be regarded as a dynamic measure of the neuromuscular function of the knee joint.

A curvilinear relationship between PTT and test occasion was observed for both experimental groups. The strength training group demonstrated a slowing of PTT while the proprioceptive training group demonstrated an improvement of PTT at 6 weeks. Both experimental groups regressed toward their baseline PTT values at the end of the 12 weeks, such as the strength training group demonstrated an improvement in PTT while the proprioceptive training group demonstrated a slowing of PTT in the latter 6 weeks.

The trends observed in the strength training group and the proprioceptive training group at 6 weeks are supported by findings of Wojtys et al.¹¹⁰. In their 6 week study, Wojtys et al.¹¹⁰ observed the time to PTT for knee flexion improved by the largest margin (38 ms) in the agility trained group compared to the isotonic or isokinetic trained group. Wojtys et al.¹¹⁰ also observed that the time to PTT for knee flexion slowed (31 ms) in the isotonic trained group. However, these observations were not statistically significant between the three groups (agility, isotonic, and isokinetic). The improvement in PTT observed by Wojtys et al.¹¹⁰ and by investigators of this study is proposed to be due to improved coordination and neural activation of the ACL reconstructed limb secondary to the prescribed proprioceptive training. Coordination is defined as highly skilled multimuscular automaticity.¹³⁶ The ability to coordinate depends on:

1. Appropriate firing and timing of specific musculature to produce the desired motor pattern.
2. Appropriate inhibition of specific musculature not involved in the desired motor pattern.
3. Practice.

The appropriate neural activation and inhibition of specific musculature relies on proprioception and kinesthesia. According to Kottke¹³⁶, the most important aspect of practice to develop coordination engram is the building of inhibition so that muscles that should not participate in the pattern are inhibited.

Wojtys et al.¹¹⁰ had difficulty explaining the slowing of PTT demonstrated by their isotonic group at the end of the 6 weeks. The findings of Wojtys et al.¹¹⁰ and of this study at 6 weeks are in contrast to those of Hakkinen and Komi⁹². Hakkinen and Komi⁹² conducted a study examining the effects of heavy resistance strength training, 3 times per week for 16 weeks, on neuromuscular performance both in voluntary and reflex contractions of the quadriceps muscle. These investigators reported an improvement in the time to peak muscle torque of the quadriceps muscle at 8 weeks and at 16 weeks. This improvement was attributed to an increase in the fast twitch/slow twitch (FT/ST) muscle area ratio. A fast motor unit produces a higher tension and reaches a peak twitch tension in a shorter time than a slow unit.⁹² A possible rationale for the slowing of PTT demonstrated by the strength training group at 6 weeks may be the lack of similarity between the training mode and the testing mode. The emphasis of the strength training program (used in this study) was to recruit the maximum number of motor units possible so that a maximum force or muscular contraction was produced. The emphasis was not on the ability to recruit maximally in a short period of time. Rather, slow concentric and eccentric contractions were emphasized. However, the testing of PTT relies on one's ability to maximally recruit their hamstring muscle in the shortest amount of time possible.

Another possible rationale for the slowing of PTT demonstrated by the strength training group at 6 weeks is a decreased sensitivity of the muscle spindles secondary to the prescribed training.⁹² In their 16 week study examining the effects of strength training, a significant decrease in reflex EMG amplitude/force amplitude ratio of the quadriceps was demonstrated. Hakkinen and Komi⁹² suggested this result may imply a change in the sensitivity of the muscle spindles. These investigators proposed that a decrease in sensitivity of the muscle spindles may result from the morphological changes

of the intrafusal fibers caused by strength training. A decrease in muscle spindle sensitivity of the hamstring muscle may ultimately affect kinesthesia (i.e. to detect stretching of the hamstring muscle) and the stiffness of the muscle, and thus, peak hamstring torque time.

The trends observed at the end of the 12 weeks are difficult to explain. It is possible that the observed improvement in PTT (from the sixth week) demonstrated by the strength training group is secondary to an increase in FT/ST area ratio, as proposed by Hakkinen and Komi⁹². As stated previously, Hakkinen and Komi⁹² observed improved PTT of the quadriceps muscle at 8 weeks while Wojtys et al.¹¹⁰ observed slowing of PTT at 6 weeks of isotonic training. It may be that an increase in FT/ST area ratio is time dependent and thus, an improvement of PTT for the strength training group was not observed until the end of the 12 weeks. An increase in FT/ST area ratio may also be dependent on the degree of overloading specified for isotonic training. Loads of 80% to 120% of one maximum repetition were used for the study conducted by Hakkinen and Komi.⁹² A maximum weight resistance tolerated for 3 sets of 10 repetitions was used by Wojtys et al.¹¹⁰ and this study. It is possible that subjects in the strength training group were unable to advance to loads similar to those used in the study by Hakkinen and Komi⁹² until the latter half of the training program. It should be noted that Hakkinen and Komi⁹² expressed the opinion that in training for longer durations (i.e. greater than 16 weeks), specific effects of heavy resistance strength training may be demonstrable by a worsening in isometric and dynamic force-time characteristics. Whether this worsening is due to decreases in the firing frequencies and/or changes in recruitment pattern of the motor units was not determined.⁹² It should be noted the lack of correlation between muscle reaction time and the strength has been documented in the literature.^{70, 137}

The observed slowing of PTT (from the sixth week) demonstrated by the proprioceptive training group may be secondary to a lack of appropriate progression of the training protocol. The proprioceptive training protocol was designed to ensure those subjects who were symptomatic (i.e. pain and swelling) in their ACL reconstructed knee could still participate. However, verbal feedback from the subjects in Group Two

indicated they felt the latter half of the proprioceptive training program to be not as challenging as the first half of the program. Secondary to the lack of challenge in the latter half of the proprioceptive training program, subjects may have lost gains made in the initial half of the program.

Another possible factor responsible for the slowing of PTT (from the sixth week) demonstrated by the proprioceptive training group at the end of the 12 weeks may be the integration of speed and complex tasks into the proprioceptive training protocol. Although the integration of speed and complexity of tasks into proprioceptive training programs for ACL deficient and ACL reconstructed knees is often perceived to be essential and appropriate in the clinical setting, an emphasis on the precision of performing tasks may be more important for regaining normal neuromuscular control.¹³⁶ According to Kottke¹³⁶, there are limits to voluntary muscular control. A person can be aware of only one muscle action or position at a time. An individual training for coordination can shift his or her attention only two to three times per second. According to Kottke¹³⁶, this means that for proper training under conscious control, the activity must be limited in complexity and performed slower compared to the rate of performance of normal automatic activity. The ultimate goal of proprioceptive training is to achieve the coordination of appropriate muscle firing patterns during functional activities without the conscious awareness of the individual. Engrams, or automatic patterns, are only established by repetitions of precise patterns of activity hundreds of thousands of times.^{136, 138} Patterns inadequately practiced results in errors of performance due to the lack of inhibition of muscles not desired in the motor pattern. In addition, incorrectly performed patterns of activity during practice develop into engrams of those incorrectly performed patterns. Finally, there is a need for perpetual practice to maintain peak performance of any engram.

Thus, the slowing of PTT observed in the proprioceptive training group at the end of the 12 weeks may not be due to the lack of progression in the latter half of the training program, but rather secondary to the inappropriate integration of speed and complexity of tasks. Since the latter half of the proprioceptive training protocol focused on these two components, the precision of performing motor tasks may have deteriorated, and a non-

optimal training environment was created. Thus, although factors such as speed, force, and complexity of tasks need to be introduced into any coordination training program, these factors should only be integrated if the precision of motor control is not compromised.

Further evidence against early introduction of speed into proprioceptive training can be found in the neurophysiology literature. Collins et al.¹³⁹ conducted a study examining our ability to detect muscle receptors' signals in different motor tasks and contexts. Although it has been demonstrated that muscle receptors play an important role in our conscious perception of movement, there is little information on our ability to detect their signals during different motor tasks. Collins et al.¹³⁹ demonstrated there was a general attenuation of sensory feedback during movement, especially when the movement was rapid and large in amplitude. This raises questions regarding the role of muscle receptors in movement control, especially during large, rapid movements. Collins et al.¹³⁹ concluded that the extent to which the nervous system gates the different sensory modalities in the same way, or differentially, depending on the sensory demands of the task at hand, requires further investigators. Based on the findings of Collins et al.¹³⁹, the early integration of speed into proprioceptive training protocols should be viewed with some caution. If the primary focus of ACL proprioceptive training protocols is to maximize the sensory information mediated by the joint and muscle receptors to dynamically stabilize the knee joint, performing tasks at slower speeds would appear to allow this goal to be achieved more effectively

As mentioned previously, no published study examining the effectiveness of proprioceptive training in the ACL reconstructed knee has used isokinetic muscle torque as an outcome measure. Results of this study indicate that proprioception training may induce strength gains in the ACL reconstructed limb.

A group by test occasion interaction effect was demonstrated on the following isokinetic variables:

1. Average concentric quadriceps torque of the ACL reconstructed limb.
2. Average eccentric quadriceps torque of the ACL reconstructed limb.
3. Average eccentric hamstring torque of the ACL reconstructed limb.

After 12 weeks of training, the proprioceptive group made greater improvements in these three isokinetic variables than the strength training group. The strength training group changed minimally after 12 weeks of training in these three isokinetic variables

The lack of greater gains in isokinetic variables for the strength training group was unexpected. From the data sheets handed in by the subjects it was evident that heavier weights were being used as the 12 weeks of training progressed. However, these improvements were not reflected in the results of isokinetic strength testing at the end of the 12 weeks. Nevertheless, the results of this study is supported by Wojtys et al.¹¹⁰. Wojtys et al.¹¹⁰ also found no significant increase in isokinetic strength in normal subjects who were placed on a 6 week isotonic training protocol. These investigators felt the lack of isokinetic change at the end of the 6 weeks in the isotonic group reflected the specificity of training and testing modes. Rasch and Morehouse¹⁴⁰ demonstrated strength gains from a 6 week training protocol in tests when muscles were employed in a familiar way, but little or no gain in strength was observed when unfamiliar test procedures were employed.

The isokinetic strength gains observed in the proprioceptive training group were surprising. These results are in contrast to those of Wojtys et al.¹¹⁰. These investigators found a lack of isokinetic change in normal subjects who were placed on a 6 week agility program, similar to that employed in this study. Possible explanations for the gains observed in Group Two are:

1. The main goal of the proprioceptive training program is to improve the neuromuscular function or the coordination of the affected lower extremity. The training of coordination is generally considered a volitional activity, during which, by trial and perception of results, an individual selects the muscular activity resulting in the desired performance.¹³⁸ Isokinetic testing, to a certain degree, relies on the coordination of the tested limb or joint. Thus, it is possible that the isokinetic changes observed in Group Two is secondary to improved coordination and better performance of the desired motor pattern compared to Group One.

2. The strength gains observed in Group Two can probably be attributed to improvements in neural activation rather than muscle hypertrophy.¹⁴¹ It is quite possible that the proprioceptive training program contributed significantly to this neural activation involved in the early stages of strength gain. The role(s) neural mechanisms play in strength increase before muscle hypertrophy can be quite extensive. Yue and Cole¹⁴² compared the maximal voluntary force production after a training program of repetitive maximal isometric muscle contraction with force output after a training program that did not involve repetitive activation of muscle; that is, after mental training. Results indicated that strength increases can be achieved without repeated muscle activation (i.e. mental training). The investigators concluded that these force gains are secondary to the practice effects on central motor programming or planning. The results of this study contribute to the existing evidence for the neural origins of strength gains that occur before muscle hypertrophy.

The following isokinetic variables were found to be significantly different after the 12 weeks of training for the ACL intact limb:

1. Average concentric torque of the quadriceps muscle.
2. Average eccentric torque of the hamstring muscle.

Both the experimental groups made similar gains in the above two isokinetic variables after 12 weeks of training. These isokinetic gains can be attributed to the following:

1. The increased frequency of physical activity (i.e. prescribed training protocol three times a week) the subjects experienced during the 12 weeks.
2. The concept of cross education.¹⁴¹ It has been suggested that the nature of cross education effect may entirely rest on neural factors presumably acting at various levels of the nervous system which could result in increasing the maximal level of muscle activation of the untrained limb.

Many studies in the literature have examined the reliability and validity of functional testing.^{123, 128, 129} Other studies have examined the correlational relationship between the ability to perform these functional tests and some factor(s).^{91,}

¹⁴³ However, we were unable to find studies examining the effects of training after ACL reconstruction on the performance of functional tests.

The results of this study indicate that both strength and proprioceptive training have beneficial effects on functional ability (SLHD and one-legged timed hop) for both the ACL reconstructed and the ACL intact limbs. The following factors have been documented in the literature to have significant effects on functional ability:

1. Concentric and eccentric peak torque of the quadriceps muscle.^{91, 144}
2. Concentric torque of the hamstring muscle.¹⁴³
3. Concentric and eccentric quadriceps work.¹⁴⁴

From the regression analyses of this study, the following factors were found to have effects on functional ability (SLHD):

1. Average concentric quadriceps torque.
2. Average eccentric quadriceps torque.
3. Average concentric hamstring torque.
4. Average eccentric hamstring torque.

Of the four isokinetic variables, average concentric hamstring torque had the most statistically significant correlational relationship with functional ability, as determined by SLHD. Thus, it is evident that isokinetic strength of the hamstring and quadriceps muscles have effects on SLHD performance. No dependent variables in this study were found to have an effect on the performance of the one-legged timed hop. These results are supported by the findings of the literature. Pincivero et al.¹⁴³ reported that concentric quadriceps and hamstring strength have a significant contribution to the one-legged single hop for distance test. They also concluded that the hamstring muscles may play a more important role during the propulsive phase, thereby enabling normal subjects to jump further. Govett⁹¹ and Wilk et al.¹⁴⁵ also demonstrated a significant effect of the concentric peak torque of the quadriceps on the performance of the SLHD.

Delitto et al.¹⁴⁴ examined the relationship between isokinetic peak torque and work of the quadriceps to one-legged single hop for distance and vertical jump in subjects who had undergone ACL reconstruction. These investigators concluded that weaker

relationships between quadriceps peak torque and quadriceps work to SLHD and vertical exist in subjects following ACL reconstruction compared to active subjects without knee pathology. They felt that performance of the SLHD and vertical hop in ACL reconstructed subjects is related to factors other than isokinetic quadriceps peak torque and work. They concluded that other factors such as stability, proprioception and confidence in the knee may be more related to the performance of the two hops. However, no statistically significant correlations were found between functional hop tests and PTT in this study.

The lack of relationship found between PTT and functional ability can be substantiated by Govett's⁹¹ results. Govett⁹¹ also found a lack of relationship between proprioception and functional ability (SLHD). It is difficult to assess the clinical relevance of the lack of relationship found between PTT and SLHD performance since PTT is only one component of the neuromuscular control involved in functional ability.

In regards to the subjective assessment and the subjective analysis of physical function of the ACL reconstructed limb, no significant difference was found between the two experimental groups. Both groups demonstrated a significant improvement in both subjective scores. These results are in agreement with the findings of Beard et al.¹⁰⁹. Beard et al.¹⁰⁹ conducted a prospective, double-blinded, randomized, clinical trial to investigate the efficiency of two rehabilitation programs (strength training and proprioceptive training) for ACL deficient limbs. Both training groups demonstrated a significant increase in subjective score (Lysholm and Gillquist Knee Scoring Scale). Beard et al.¹⁰⁹ also demonstrated that the change in subjective score was significantly greater in the proprioceptive group than the strength training group. The lack of significance found between the two experimental groups may be secondary to the different population involved in this study.

In conclusion, peak hamstring torque time of the ACL reconstructed limb was influenced by both strength training and proprioceptive training. It is proposed that the two types of training influence PTT through different neuromuscular mechanisms. A group by test occasion interaction effect was found on isokinetic strength measures. The proprioceptive group demonstrated greater gains in the average concentric and eccentric

quadriceps torques and the average eccentric hamstring torque of the ACL reconstructed limb after 12 weeks of training, while minimal change was observed in the strength training group after 12 weeks. Both groups demonstrated improved functional ability in the lower extremities after 12 weeks of training. Both experimental groups also demonstrated significant gains in the subjective assessment and the subjective analysis of physical function of the ACL reconstructed limb.

Limitations

Several limitations should be considered for this study.

Threats to Statistical Conclusion Validity:

1. **Sample Size:** The sample size used in this study is small. Smaller samples are less likely to be a good representation of population characteristics, and, therefore, true differences between groups are less likely to be recognized. A power analysis^c was performed prior to the start of the study to estimate the sample size required. The power analysis indicated that a sample size of 10 subjects would provide sufficient power levels to detect a difference between groups and an interaction effect, but not for a difference between test occasions. Thus, a sample size of 10 subjects was used for this study.

A second power analysis was performed after the completion of the study (Appendix A). Based on the results of the second power analysis, a sample size of 10 subjects provided an extremely high power level for the interaction effect, but very low power levels for the main effects (i.e. experimental group and test occasion). Thus, it is highly probable that the insignificant findings found between groups and test occasions are due to the small sample size used. However, the results of this study did demonstrate the interaction effect between group and test occasion. Statistically, an interaction effect (when present) must be interpreted before conclusions can be made for the main effects. Therefore, although this study failed to demonstrate significant main effects, it still provided important information regarding the effects of proprioceptive and strength training on PTT in the ACL reconstructed limb by demonstrating the interaction effect.

Threats to Internal Validity:

1. **Lack of a Control Group:** Due the ethical reasons, a control group was not established in this study. Without a control group, however, it becomes difficult to be confident that the changes observed in the dependent variables are secondary to the prescribed intervention or are simply due to the passage of time (from surgery).

^c This power analysis was performed based on estimated values for the peak hamstring torque time variable. Of all the dependent variables in this study, we were most interested in the PTT variable.

2. Attrition: Significant attrition introduces bias by changing the composition of the sample. Attrition was controlled in this study by maintaining an encouraging environment. No subject was lost to attrition in this study.
3. Compliance: Compliance is always an issue when specific instructions must be carried out by subjects involved in a study. Compliance was controlled by the following means:
 - a. The exercise sessions were supervised whenever possible.
 - b. When a supervised session was not possible, subjects were asked to record the details of the session. This record was later collected by the investigator(s).
3. Selection: The subjects involved in this study may be highly motivated individuals who do not represent the average person with an ACL reconstructed knee. Subjects involved in this study were asked to commit approximately 3.5 to 4 hours a week to their exercise protocol. The average individual may not be motivated to commit this amount of time per week to rehabilitate their ACL reconstructed knee.

Threats to External Validity

1. Surgical Technique: There are many surgical techniques used to reconstruct the torn ACL. In addition, the same surgical technique performed by different surgeons may have slightly different outcomes or effects. Thus, the conclusions of this paper are applicable to the surgical technique used in this study.
2. Measurement of PTT: Peak hamstring torque time of the ACL reconstructed limb was assessed in the seated position. Measuring peak hamstring torque time in the seated position may limit the ability to generalize the results to more dynamic conditions, such as walking and running. It is unclear at the present time whether PTT measured in the seated position correlate well with those measured in the standing position. Kiefer et al.¹⁴⁶ reported that reproduction of passive joint position scores in sitting should not be compared to those performed in standing. In addition, the use of electromyograph while measuring PTT would have provided a more detailed description of the neuromuscular function of the ACL reconstructed limb.

Chapter Nine

SUMMARY AND CONCLUSION

Summary

The anterior cruciate ligament is the most commonly injured ligament in sports. Despite extensive research to date, the management of ACL injuries is still not to the point where the function of the affected knee can be completely restored.

The ACL plays a major role in maintaining the normal function of the knee joint. When the ACL is disrupted, the knee joint loses both an important mechanical restraint and a source of sensory input for joint proprioception and kinesthesia. Thus, decreased stability of the knee associated with functional disability is a common feature after ACL injuries.

Despite the extensive research done on the sensory function of the ACL, it is unclear as to what degree the biomechanics of the knee joint and vulnerability of its ligaments are dependent on its innervation. In addition, although ACL reconstructions are now commonly performed in young athletes, the effects of surgical reconstruction on the proprioceptive function of the affected knee remain unclear. Current research findings on the effects of ACL reconstruction on knee proprioception provide no consensus. In addition, the clinical significance of statistical differences of proprioception as determined in research studies is undetermined.

Currently, proprioceptive training is thought to be an important component in the rehabilitation of ACL injuries. However, the effectiveness of proprioceptive training is not elucidated in the literature.

The main purpose of this study was to examine the effectiveness of proprioceptive training in the ACL reconstructed knee. Rather than choosing the more commonly used measures of proprioception and kinesthetic awareness (i.e. detection of passive joint motion, reproduction of passive joint position), a more dynamic measure of knee neuromuscular function was chosen. Peak torque time is a measure of volitional activity of muscle(s) and we propose it relies on the following factors:

1. The sensitivity of the muscle spindles.
2. Kinesthetic awareness of the knee joint.
3. The ability to recruit as many motor units as possible in the shortest amount of time.

4. The coordination of the limb to the specified task.

It is the postulation of this study that there is sensory information originating from the ACL graft and joint afferents that affects the primary muscle spindle afferents via the gamma efferent muscle spindle system. Thus, the ACL graft may contribute to the continuous preparatory adjustment of muscular stiffness through the gamma efferent muscle spindle system. PTT can be regarded as the ability of the hamstring muscle to increase its stiffness at the time of a displacement (i.e. the forward movement of the dynamometer lever arm). As indicated in the review of the literature, functional joint stability is greatly determined by joint load caused by the contraction (or stiffness) of its surrounding muscles. Hence, PTT can be regarded as a dynamic measure of the neuromuscular function of the knee joint.

A second purpose of the study was to determine the relative contribution of isokinetic strength and peak hamstring torque time to functional ability. Functional ability was determined by two functional hop tests: one-legged single hop for distance and one-legged timed hop.

Two experimental groups of five subjects were compared. Group One (Strength Training Group) was placed on a 12 week strength training protocol for the lower extremities. Group Two (Proprioception Training Group) was placed on a 12 week proprioceptive protocol for the lower extremities.

At the end of the 12 weeks, there was no significant difference in PTT between or within (between test occasions) the two experimental groups. A curvilinear relationship was observed between PTT of the ACL reconstructed limb and test occasion for both experimental groups. There was a significant group by test occasion interaction effect on PTT of the ACL reconstructed limb. The strength training group demonstrated a slowing of PTT while the proprioceptive group demonstrated an improvement in PTT at the end of 6 weeks. At the end of the 12 weeks, both experimental groups regressed toward their baseline PTT values, such as the strength training group demonstrated an improvement in PTT while the proprioceptive group demonstrated a slowing of PTT in the latter 6 weeks. It is proposed that the two types of training influence PTT through different neuromuscular mechanisms.

There was a significant group by test occasion interaction effect on isokinetic strength measures of the ACL reconstructed limb. The proprioceptive training group demonstrated greater gains in average concentric and eccentric quadriceps torques and average eccentric hamstring torque of the ACL reconstructed limb than the strength training group after the 12 weeks. The greater gains observed in the proprioceptive training group at the end of the 12 weeks are proposed to be secondary to improved coordination of the ACL reconstructed limb, improved neural activation of the ACL reconstructed limb, and better performance of the desired motor pattern on the KIN-COM rather than actual muscle hypertrophy.

Both experimental groups demonstrated similar gains in the subjective assessment and the subjective analysis of physical function of the ACL reconstructed limb. Both experimental groups also demonstrated similar gains in the functional ability, as determined by the two functional hop tests, of the ACL reconstructed limb after 12 weeks of training.

Regression analyses found average concentric and eccentric torques of the quadriceps and hamstring muscle to have significant effects on the performance of the one-legged single hop for distance. No significant effects were found for any of the dependent variables on the performance of the one-legged timed hop.

However, due to the small sample size used in this study, the ability to generalize the results of this study may be limited.

Conclusion

Based on the findings of this study, the following conclusions (as pertaining to the ACL reconstructed knee) can be made based on the hypotheses set for this study:

1. Both training protocols had beneficial effects on the subjective assessment and the subjective analysis of physical function of the ACL reconstructed knee.
2. The proprioceptive training group made greater isokinetic gains after 12 weeks of training compared to the strength training group. However, these isokinetic gains observed in the proprioceptive training group are probably secondary to improved coordination, improved neural activation, and better performance of the desired motor pattern on the KIN-COM rather than actual muscle hypertrophy.
3. Both training protocols had beneficial effects on the performance of the two functional hop tests.
4. There was no significant difference between or within (between test occasion) the two experimental groups in PTT. There was, however, a significant group by test occasion interaction effect on PTT. A curvilinear relationship between PTT and test occasion was observed for both groups. Further investigations are necessary to clarify the trends observed. It is proposed that the two training protocols influence PTT through different neuromuscular mechanisms. Strength training is proposed to positively influence PTT by increasing FT/ST muscle area ratio and to negatively influence PTT by decreasing muscle spindle sensitivity. Proprioceptive training is proposed to positively influence PTT by improving coordination and improving neural activation and inhibition of the appropriate muscles. However, the effectiveness of proprioceptive training is dependent on appropriate progression and repetition. Early integration of speed, force, and complexity of tasks into proprioceptive training may decrease the effectiveness of training. Integration of these components should only occur if the precision is not compromised.
5. Average concentric and eccentric torques of the quadriceps and hamstring muscles had significant effects on the performance of the one-legged single hop for distance test. Average concentric hamstring torque had the most statistically significant correlational relationship with functional ability (SLHD).

Chapter Ten

CLINICAL RELEVANCE AND RECOMMENDATIONS

Clinical Relevance

The purpose of conducting clinical studies is to gain insight into clinical practices. Currently, proprioceptive training is emphasized in the literature as an important component of rehabilitation after ACL injuries. However, the effectiveness of proprioceptive training in the ACL reconstructed limb is not well documented. In addition, there is little discussion in the literature regarding the appropriate progression of proprioceptive training after ACL injuries.

The results of this study indicate that both strength training and proprioceptive training are beneficial for the ACL reconstructed limb. Proprioceptive training is more effective than strength training in restoring the coordination of the ACL reconstructed limb. However, to ensure the effectiveness of proprioceptive training, appropriate progression and repetition are essential. Early integration of speed, force, and complexity of tasks into proprioceptive training protocols may decrease the effectiveness of training. Integration of these components should only occur if the precision of motor control during tasks is not compromised.

Recommendations

The following recommendations are proposed for future studies:

1. This study only involved subjects with ACL reconstructed limbs. To determine the effects of ACL reconstruction on proprioception, it is recommended that future prospective studies involve subjects with ACL deficient limbs also.
2. This study measured dynamic neuromuscular function in the seated position. Measuring dynamic neuromuscular function in the seated position may limit the ability to generalize the results to more dynamic conditions, such as walking and running. Therefore, it is recommended that future studies measure dynamic neuromuscular function in the standing position. In addition, the use of electromyograph would provide a more detailed description of neuromuscular function.
3. This prospective study used a small sample size. A small sample size is less likely to be good a representation of population characteristics. In addition, the power level for the main effects in the study were very low. Therefore, it is the recommendation that future studies use a larger sample size.

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Appendix A
POWER ANALYSIS

Power Analysis #1

A power analysis was performed prior to the start of the study to determine the number of subjects required. The power analysis performed was based on estimated values for the peak hamstring torque time variable. The following equations were used:

$$1. L_A = n * q * \frac{\text{the sum of } (u_i - u.)^2}{\sigma^2 * [1 + (q-1) * \rho]}$$

Where L_A = The difference between test occasion.

Where n = The number of subjects per cell.

Where q = The number of test occasions.

$$2. L_B = n * p * \frac{\text{the sum of } (u_j - u.)^2}{\sigma^2 * (1 - \rho)}$$

Where L_B = The difference between groups.

Where p = The number of groups.

$$3. L_{AB} = n * \frac{\text{the sum of } (u_{ij} - u_i - u_j + u.)^2}{\sigma^2 * (1 - \rho)}$$

Where L_{AB} = The interaction effect between group by test occasion.

Values for σ and ρ were estimated from those in the literature and the pilot study results. Changes in peak hamstring torque time over the 12 week period were also estimated from those in the literature.

The results for L_A , L_B , and L_{AB} were:

$L_A = 0.92$ when n is 5. Power is 0.1316.

$L_B = 36.90$ when n is 5. Power is 0.9998.

$L_{AB} = 12.83$ when n is 5. Power is 0.8900.

Since the power levels were high for L_B and L_{AB} when n is 5, a sample size of 10 was chosen for this study.

Power Analysis #2

A second power analysis was performed after the completion of the study to determine the actual power levels of the study.

The results for L_A , L_B , and L_{AB} were:

$L_A = 1.95$ when n is 5. Power is 0.2251.

$L_B = 2.06$ when n is 5. Power is 0.1929.

$L_{AB} = 47.71$ when n is 5. Power is >1.9999 .

Appendix B
SUBJECTIVE RATING SCALES
&
SUBJECTIVE ASSESSMENT SHEET

Table B1. Modified Lysholm and Gillquist Knee Scoring Scale

Limp (5 points)	
None	5
Slight or periodical	3
Severe and constant	0
Support (5 points)	
None	5
Stick or crutch	2
Weight-bearing impossible	0
Locking (15 points)	
No locking and no catching sensations	15
Catching sensation but no locking	10
Locking	
Occasionally	6
Frequently	2
Locked joint on examination	0
Instability (25 points)	
Never giving away	25
Rarely during athletics or other severe exertion	20
Frequently during athletics or other severe exertion (or incapable of participation)	15
Occasionally on daily activities	10
Often in daily activities	5
Every step	0
Pain (25 points)	
None	25
Inconstant and slight during severe exertion	20
Marked during severe exertion	15
Marked on or after walking more than 2 km	10
Marked on or after walking less than 2 km	5
Constant	0
Swelling (10 points)	
None	10
On severe exertion	6
On ordinary exertion	2
Constant	0
Stair-climbing (10 points)	
No problems	10
Slightly impaired	6
One step at a time	2
Impossible	0
Squatting (5 points)	
No problems	5
Slightly impaired	4
Not beyond 90°	2
Impossible	0

Table B2. Tegner and Lysholm Activity Scale

10. Competitive sports Soccer - national and international elite	5. Work Heavy labor (e.g. building, forestry) Competitive sports Cycling Cross-country skiing Recreational sports Jogging on uneven ground at least twice weekly
9. Competitive sports Soccer, lower divisions Ice hockey Wrestling Gymnastics	4. Work Moderately heavy labor (e.g. truck driving, heavy domestic work) Recreational sports Cycling Cross-country skiing Jogging on even ground at least twice weekly
8. Competitive sports Bandy Squash or badminton Athletics (jumping, etc.) Downhill skiing	3. Work Light labor (e.g. nursing) Competitive and recreational sports Swimming Walking in forest possible
7. Competitive sports Tennis Athletics (running) Motorcross, speedway Handball Basketball Recreational sports Soccer Bandy and ice hockey Squash Athletics (jumping) Cross-country track findings both recreational and competitive	2. Work Light labor Walking on uneven ground possible but impossible to walk in forest
6. Recreational sports Tennis and badminton Handball Basketball Downhill skiing Jogging, at least five times per week	1. Work Sedentary work Walking on even ground possible 0. Sick leave or disability pension because of knee problems

***THE EFFECTIVENESS OF PROPRIOCEPTION TRAINING IN THE ACL
RECONSTRUCTED KNEE***

SUBJECT INFORMATION SHEET

1. Subject ID: _____
2. Date of Birth: _____
3. Age: _____
4. Sex: Female / Male
5. Height: _____
6. Weight: _____
7. Knee Involved: Left / Right, Dominant / Non-dominant
8. Date of Injury: _____
9. When were you first diagnosed with an ACL tear? _____
10. Date of Surgery: _____
11. Surgeon: _____
12. What was your physical activity level prior to this injury? _____
(Use the Tegner and Lysholm Activity Scale)
13. Please describe the physical activities your were involved in prior to this injury.
Type: _____

Frequency (per week): _____

14. Please describe the physical activities your are currently involved in.
Type: _____

Frequency (per week): _____

-
15. Does the above activities (question 14) cause pain and/or swelling in your ACL reconstructed knee? If so, please indicate how long these episodes (of pain and swelling) last for.
-
-

16. Please describe the physiotherapy (if any) you received for your injured knee prior to surgery. Please include the length of time (in weeks) you received physiotherapy and the frequency (per week) of your visits.
-
-
-
-

17. Please describe the physiotherapy (if any) you received after your surgery. Please include the length of time (in weeks) you received physiotherapy and the frequency of your visits (per week).
-
-
-
-

18. Please describe any other treatments (e.g. massage therapy) you have received for your injured knee. Please include the length of time (in weeks), frequency (per week) and indicate whether it was before and/or after surgery you received such treatment(s).
-
-
-
-

19. How was your anterior cruciate ligament injured (if known)?
-
-

20. Have you ever been diagnosed by a physician to have an arthritic condition involving your legs? If so, please indicate the date you were diagnosed and the type of arthritis.
-
-
-

21. Have you ever been diagnosed by a physician to have a neurological condition or disease (e.g. multiple sclerosis)? Is so, please indicate the date you were diagnosed and the condition.

22. To the best of your knowledge, do you have any cardiovascular, respiratory, systemic, metabolic condition that may limit your exercise tolerance? Is so, please explain.

23. Do you have pain and/or swelling in your ACL reconstructed knee during normal activities of daily living? If so, please indicate the frequency (per week) you experience such episodes.

Appendix C
TRAINING PROTOCOLS

Table C1: Exercise Protocol for Group One (Strength Training)

Week 1 - Week 12

1. Stationary bike. Cycle for 15 minutes at tension appropriate for individual.
 2. Leg press exercises. 3 sets of 10 repetitions. Load will be 70% to 80% of one-repetition maximum (1-RM).
 3. Hamstring curls. 3 sets of 10 repetitions. Load will be 70% to 80% of 1-RM.
 4. Lunges. 3 sets of 10 repetitions. Load as appropriate for individual.
 5. Calf raises. Load as appropriate for individual.
 6. Half-squats. 3 sets of 10 repetitions. Load as appropriate for individual.
 7. Hip abduction exercises. 3 sets of 10 repetitions. Load as appropriate for individual.
 8. Hip adduction exercises. 3 sets of 10 repetitions. Load as appropriate for individual.
-

Table C2: Exercise Protocol for Group Two (Proprioceptive Group)

Week 1 - Week 2

1. Stationary Bike. Cycle for 15 minutes at tension appropriate for individual.
2. Eccentric hamstring control using exercise tubing. Allow the use of ski poles for balance. 3 sets of 10 repetitions.
3. Circular wobble board. Two legs for 5 minutes with eyes opened. Rest. One leg for 2 minutes (2 repetitions).
4. Wheeled board. Sitting. Affected leg on the wheeled board. Eyes closed. Sudden forward force applied by investigator, subjects attempts to stop the board's movement as soon as possible by using their hamstring muscle. A session of 5 minutes.
5. Wheeled board. Standing. Affected leg on the wheeled board. Eyes closed. Sudden forward force applied by investigator, subjects attempts to stop the board's movement as soon as possible by using their hamstring muscle. A session of 5 minutes.
6. Fitter board. Both legs on the Fitter. Movement pattern is forwards and backwards. One session of 5 minutes with the right leg placed forward. One session of 5 minutes with the left leg placed forward. Eyes opened. Allow the use of the ski poles.
7. Step overs on a wooden box. Start on Week 2. Three patterns of movement. Each movement consists of 60 repetitions.
8. Carrioca. Both directions. 6 sets of 5 repetitions.

Week 3 - Week 4

1. As above.
2. Eccentric hamstring control using exercise tubing. Increase to 4 sets of 10 repetitions.
3. Circular wobble board. Week 3: Affected leg standing for 2 minutes. Eyes opened. Forward 747 on the affected leg for 5 minutes. Eyes opened. Week 4: Eyes opened for all tasks. Forward 747 for 5 minutes. Reverse 747 for 5 minutes.
Rectangular board. Both legs on the board. Balance is forwards and backwards. Eyes opened. One session of 2 minutes with the right leg forward. One session of two minutes with the left leg forward.
4. Wheeled board. Sitting. Week 3: 2 minute session. Week 4: Discontinue.
5. Wheeled board. Standing. Week 3: As above. Week 4: Eyes closed.
6. Fitter. Week 3: As above. Wean from ski poles if able. Week 4: Eyes closed.
7. As above.
8. As above.
9. Hopping patterns. Week 3: Side to side. Affected leg only. 50 repetitions. Week 4: Forward and backward. 2 legs. 20 repetitions.
10. Squat on square balance board.

Week 5 - Week 6

1. As above.
2. As above.
3. Circular wobble board. Eyes closed for all tasks. Affected leg standing for 2 minutes. Forward 747 for 5 minutes. Reverse 747 for 5 minutes.
Rectangular board. As above.
4. Discontinued.
5. As above.
6. Fitter. Affected leg standing for 5 minutes. Eyes opened. Allow use of ski poles.
7. As above.
8. Carrioca. Week 5: As above. Week 6: A drill session of 5 minutes. Each drill is approximately 35 seconds.
9. Hopping Patterns. As above. Week 5: Square pattern hop. Two legs. 20 repetitions. Week

6: Triangular pattern hops. Two legs. 20 repetitions in total.

10. As above

Week 7 - Week 8

1. As above.

2. As above.

3. Circular wobble board. Eyes closed for all tasks. Forward 747 for 5 minutes. Reverse 747 for 5 minutes. Play catch for 5 minutes, standing on the affected leg only.

Rectangular board. As above. Eyes closed for all tasks.

4. Discontinued.

5. As above.

6. Fitter. Affected leg standing for 5 minutes. Eyes opened. No poles.

7. As above.

8. As above.

9. Hopping patterns. As above. "X" pattern hops. 20 repetitions in total.

10. As above.

Week 9 - Week 10

1. As above.

2. As above.

3. Circular wobble board. As above.

Rectangular board. As above. Play catch for 5 minutes (balance is side to side).

4. Discontinued.

5. As above.

6. Fitter. As above. Eyes closed. Poles as necessary. Side to side movement (2 legs) with eyes opened for 5 minutes. No poles.

7. As above.

8. As above.

9. Hopping Patterns. As above. Week 9: 12 meter straight hop forwards (2 legs). Week 10: 12 meter straight hop backwards (2 legs).

10. As above.

Week 11 - Week 12

1. As above.

2. As above.

3. Circular wobble board. Discontinue above except for playing catch for 5 minutes. Affected leg standing. 3 positions, 5 seconds each, for a total of 5 minutes. Eyes closed.

Rectangular wobble board. Discontinue above except for playing catch for 5 minutes. Play catch with balance forwards and backwards. One session of two minutes with the right leg forward. One session of two minutes with the left leg forward.

4. Discontinued.

5. As above.

6. Fitter. Week 11: As above. Week 12: Eyes closed for all tasks.

7. As above.

8. As above.

9. Hopping patterns. As above. Week 11: 12 meter zig-zag forward hop (2 legs). Week 12: 12 meter zig-zag backward hop (2 legs).

10. As above.

Appendix D
RELIABILITY OF SYMMETRY INDEXES

The following formula was used to calculate Intraclass Correlation Coefficient (ICC):

$$ICC(3,k) = \frac{BMS - EMS}{BMS}$$

The following Intraclass Correlation Coefficients were calculated for absolute torque values and symmetry indexes:

1. Average concentric quadriceps torque of the ACL reconstructed limb = 0.97.
2. Average eccentric quadriceps torque of the ACL reconstructed limb = 0.91.
3. Average concentric quadriceps torque of the ACL intact limb = 0.97.
4. Average eccentric quadriceps torque of the ACL intact limb = 0.90.
5. Average concentric hamstring torque of the ACL reconstructed limb = 0.93.
6. Average eccentric hamstring torque of the ACL reconstructed limb = 0.96.
7. Average concentric hamstring torque of the ACL intact limb = 0.98.
8. Average eccentric hamstring torque of the ACL intact limb = 0.98.
9. Concentric symmetry index for the quadriceps = 0.85.
10. Eccentric symmetry index for the quadriceps = 0.62.
11. Concentric symmetry index for the hamstring = 0.57.
12. Eccentric symmetry index for the hamstring = 0.81.