THE UNIVERSITY OF MANITOBA

FLEXIBILITY MEASUREMENT OF THE KNEE FLEXORS: A COMPARISON OF THREE CLINICAL TESTS AND ISOKINETIC DYNAMOMETRY

By

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A Thesis Study
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Dedication

I dedicate this thesis to my family, especially my parents, who have stood behind me and supported me throughout my scholastic career, and to Amber, for her support, understanding and sleepless nights. Thank you all very much.

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Abstract

FLEXIBILITY MEASUREMENT OF THE KNEE FLEXORS: A COMPARISON OF THREE CLINICAL TESTS AND ISOKINETIC DYNAMOMETRY

The high incidence of recurrent hamstring injuries in sport, especially in the recent Summer Olympics, calls into question the accuracy of current measures of injury rehabilitation. Strength and flexibility differences between healthy and previously hamstring-injured athletes have been reported in the literature, but many studies have found no significant differences between the two groups using similar testing methods. Studies of the passive properties of skeletal muscle have reported the resistance to passive knee extension using a Kin/Com isokinetic dynamometer. Comparison of this flexibility measurement technique to other, more common measures of flexibility is not well documented in the literature. Also, there is little information in the literature with respect to the passive properties of in vivo skeletal muscle with a previous strain injury.

The purpose of this study was to compare the measurement of flexibility by a Sit and Reach Test, Active Knee Extension Test, and Passive Knee Extension Test with the resistance to stretch during passive extension of the knee, as measured by the Kin/Com Isokinetic Dynamometer. A sub-problem was to examine the differences in flexibility measurement scores between individuals with a previous hamstring injury and individuals with no history of hamstring pathology.

Twenty male varsity athletes from the University of Manitoba Football and Track teams participated in the study. Subjects in the Injured Group (N=10) had sustained a hamstring strain injury within the 18 months prior to the study, while subjects in the Non-injured Group (N=10) had no history of hamstring strain injury. All subjects were injury-free and competing in their sport at the time of the study. Non-injured subjects were matched with Injured subjects according to sport, position, weight, height and limb dominance. The Non-injured group limbs were separated into 'injured' and 'uninjured' groups according to the injured and uninjured limbs of their Injured matched pair. Data collection and comparisons were conducted using the dependent variables of passive peak torque, angle at passive peak torque, maximal stiffness, and stiffness in a common range.

Regression analysis comparing the three clinical tests to the resistance to stretch variables resulted in significant correlations ($p<0.05$) between the Sit and Reach Test and the angle at peak torque, maximal stiffness, and common stiffness, between the Active Knee Extension Test and the angle at peak torque and common stiffness, and between the Passive Knee Extension Test and the angle at peak torque and common stiffness. The results indicate that the Kin/Com Dynamometer test is a valid measure of hamstring flexibility. Two-way ANOVA comparing results of the flexibility tests scores and dependent variables of the Kin/Com between Injured and Non-injured groups revealed significant differences in Active Knee Extension scores and maximal stiffness ($p<0.05$). The Injured group had significantly less flexibility, as measured by Active Knee Extension, and significantly higher stiffness in the final range passive extension of the knee in both limbs than the Non-injured group. There were no other significant differences between the groups.

The results of this study suggest that functional differences may still exist between injured and non-injured athletes even after return to full activity. Also, the Kin/Com Isokinetic Dynamometer may be a valuable tool for evaluating hamstring strain injury rehabilitation, but further investigation is required to confirm these results.

FLEXIBILITY MEASUREMENT OF THE KNEE FLEXORS: A COMPARISON OF THREE CLINICAL TESTS AND ISOKINETIC DYNAMOMETRY

CHAPTER 1

Introduction

With the large number of hamstring injuries among sprinters during the recent Olympic games in Sydney, such as Canadians Bruny Surin and Kate Anderson and Americans Inger Miller, Gail Devers, and Colin Jackson, a question arises as to the accuracy of current measures of the effectiveness of muscle injury rehabilitation. Most of these athletes have suffered similar hamstring injuries in previous years. Certainly the pressure to run in a big event when an injury is not fully healed can predispose an athlete to a recurrent strain, however, strains can recur even when the injured limb is considered fully rehabilitated (Worrell, 1994; Devlin, 2000). A full and pain-free range of motion, as well as full strength, are common guidelines in rehabilitation for return to activity, and accurate assessment of flexibility is critical to these guidelines (Worrell & Perrin, 1992; Anderson & Hall, 1995; Andrews et al, 1998).

Numerous studies have attempted to identify those athletes at a greater risk of sustaining a hamstring strain injury, with a focus on strength and flexibility differences between previously-injured and healthy athletes (Bruce, 1989; Paton et al, 1989; Worrell et al, 1991; Hennessy & Watson, 1993; Orchard et al; 1997; Bennell et al, 1998). Worrell et al (1991) found significant differences in hamstring flexibility between injured and non-injured athletes using the Passive Knee Extension test, however, other studies have shown no differences using similar flexibility tests (Bruce, 1989; Hennessy & Watson, 1993; Orchard et al, 1997). It must be noted that during passive extension of the knee, the therapist controls joint range of motion, so force application is judged subjectively by both the therapist and the athlete.

A study by Orchard et al (1997) found significant differences in isokinetic knee flexor strength between subjects with and without a history of hamstring injuries, stating that it was possible to identify athletes at risk for injury with preseason isokinetic testing. Similar results were noted by Jonhagen et al (1994). However, other studies (Bruce, 1989; Paton et al, 1989; Worrell et al, 1991; Hennessy & Watson, 1993; Bennell et al, 1998) found no significant differences in concentric and eccentric strength between previously injured athletes and athletes with no history of hamstring injury. Paton et al (1989) stated that moderate-major hamstring injuries would respond to rehabilitation programs with no permanent functional damage, however the authors did not address flexibility issues.

Comparisons of different tests that measure hamstring flexibility have been performed (Cameron & Bohannon, 1993; Gajdosik et al, 1993). Gajdosik et al (1993) compared the hip flexion angles between different protocols of the Straight Leg Raise Test; as well the knee flexion angles between the Active Knee Extension Test and the Passive Knee Extension Test. Significant differences between the knee flexion angle tests were found, but no significant differences between the hip flexion tests were noted. The authors also found significant relationships among all four tests, concluding that all of the tests probably represent similar, but indirect measures of the length of the hamstrings. Cameron & Bohannon (1993) found similar results, noting a significant relationship between the active knee extension and the active straight leg raise tests. The authors concluded that the active knee extension test is a useful alternative to the active straight leg raise, with both tests providing an indication of hamstring muscle length.

In recent years, the passive properties of skeletal muscle have been determined both in vitro (Taylor et al, 1990; Noonan et al, 1993; Best et al, 1994) and in vivo (Magnusson, 1998). Specific passive properties of skeletal muscle include the response to lengthening at different loading rates, response to static stretch, force required to stretch a muscle to failure in vitro, and changes in response to stretch due to passive warming, warm-up, and strength and flexibility training. Investigators can employ the use of a force transducer to measure both the tensile forces of skeletal muscle in vitro and the tendency to resist joint rotation in vivo.

Many in vivo investigations have focussed on the passive properties of human hamstring muscles in reaction to various stretching parameters (McHugh et al, 1992; Magnusson et al, 1995a; Magnusson et al, 1996a; Magnusson et al, 1996b; Klinge et al, 1997; Halbertsma et al, 1999; Lee & Munn, 2000). These investigations used a dynamometer to measure passive resistance to joint rotation, with different protocols employed (Magnusson, 1998; Strauss, 2000). The load cell of the dynamometer is used to detect the changes in torque output during passive extension of the knee. As the knee approaches full extension, the torque output increases, even after the moment of the weight of the leg has been accounted for and removed. This increase in torque output is called the resistance to passive stretch, as it is the resistance of the passive tissues of the knee joint (ligaments, tendons, joint capsule, muscle proteins, etc) to stretch (McHugh et al, 1992; Magnusson, 1998).

Although the use of dynamometry in the assessment of knee flexor passive resistance to knee extension has been documented, there is little information describing the correlation of its use to other clinical measures of knee flexor flexibility or in the assessment of individuals with previous leg muscle strain injury.

Ainslie & Beard (1996) used a Kin/Com dynamometer to quantify the passive resistance of the quadriceps muscles in an athlete with a unilateral hamstring injury. The case study found that the increase in resistance during passive knee flexion occurred earlier in the injured leg than in the noninjured limb. The authors attributed this resistance to movement to an increase in the passive resistance of the quadriceps. The authors recommended further investigation to determine the validity and reliability of the KINCOM as an outcome measurement tool for passive muscle resistance.

As there is little information in the literature with respect to the passive properties of muscle involved in previous hamstring injuries, it is necessary to investigate this area to determine if there are different tensile properties associated with hamstring injury. In addition, there are no studies in the literature comparing passive properties of skeletal muscle in vivo and different clinical and field measures of hamstring flexibility.

Statement of the Problem

The purpose of this study was to compare the measurement of knee flexor (hamstring) flexibility by four different methods of flexibility assessment. Specifically, the Sit and Reach Test, Passive Knee Extension Test, the Active Knee Extension Test and the passive torque of the knee flexors as measured by the Kinetic Communicator (Kin/Com) Isokinetic Dynamometer.

A sub-problem was to examine the differences in flexibility measurement scores between individuals with a previous hamstring strain and individuals with no history of hamstring pathology.

Null Hypotheses

The null hypothesis for this study was that there would be no significant correlation between the measurements of flexibility obtained from the Sit and Reach, Passive Knee Extension, and Active Knee Extension Tests, and the passive resistance of the knee flexors. In addition, there would be no difference between subjects in the control group and the experimental group or between limbs across all tests.

Delimitations

1. All subjects tested in the study were athletes with no history of hamstring injury, or those athletes who have sustained a previous unilateral hamstring injury. All subjects were free of lower limb pathology at the time of testing.
2. All subjects were participating in their sport or activity at the time of the study.
3. Subjects in the experimental group were athletes that had been diagnosed by a physician/physiotherapist/certified athletic therapist as having a hamstring muscle strain and were considered fully rehabilitated to the extent of returning to their activity at the time of testing.
4. The same investigator measured each subject with the same instruments during the same test session.
5. Three trials were used during the testing of the athletes, with the average of the two closest scores recorded as the final measurement.

Limitations

1. Subjects may not have been fully rehabilitated at the time of testing.
2. Subjects may have inadvertently contracted the hamstrings during passive testing, producing higher passive resistance values.
3. Subjects may have had different pain/discomfort thresholds, leading to earlier stopping of range of motion testing.

Significance

With the high incidence of recurrent hamstring strains among athletes at all levels, it was apparent that current rehabilitation outcome measures (flexibility, strength) were not sensitive enough to predict the recurrence of injury. It was hoped that the present study would demonstrate the high quality of the information obtained by a dynamometer and its value as a sensitive assessment tool for the measurement of rehabilitation progress and the nature of a previous injury.

A comparison of these flexibility tests and passive isokinetic dynamometry had not been reported in the literature. The purpose of this study was to further investigate the use of an isokinetic dynamometer in the evaluation of the stiffness of the knee flexors, and how this evaluation relates to other clinical measures of knee flexor length. An isokinetic dynamometer may provide a more valid and reliable measurement of the passive resistance of the hamstrings than other, more subjective tests.

The results of this study may also be useful in refining some gravity compensation protocols employed in seated isokinetic testing. By studying the resultant passive resistance curves generated by the KINCOM, investigators may have a clearer picture of the range of motion during which the resistance of the hamstrings is minimal as the knee extends from a position of 90 degrees flexion. Then, the lower limb could be positioned as close to horizontal as minimal hamstring resistance will allow in order for the dynamometer to obtain an accurate measurement of the lower limb's weight.

Definition of Terms

Active Stretching The stretching of muscle-tendon units and ligaments resulting from active development of tension in the antagonist muscles (Hall, 1999).

Axis of Rotation Imaginary line that is perpendicular to the plane of motion and passes through the centre of rotation (Hall, 1999).

Centre of Mass Point about which all the mass and weight of a body is equally balanced in all directions (Hall, 1999).

Energy Defined as the area under a Torque-Angle curve, and refers to the energy absorbed by the tissue during loading (Magnusson, 1998). Energy is measured in joules (J).

Gravity Compensation Correcting joint torque values for the weight of the limb segment due to gravity. The moment due to the weight of the limb may be calculated by direct measurement of the gravitational moment of the limb using an isokinetic dynamometer, or by estimation from anthropometic data (Kellis & Blatzopoulos, 1996).

Isokinetic Dynamometer A device, such as the Kin/Com isokinetic dynamometer, designed to match the motive torque applied while maintaining a constant angular speed of a joint movement (Kreighbaum & Barthels, 1990).

Moment Arm Perpendicular distance from the line of action of a force to the axis of rotation (Hall, 1999).

Passive Stretching The stretching of the muscle-tendon unit and ligaments resulting from a stretching force other than tension in the antagonist muscles, such as gravity, a therapist, or a dynamometer (Hall, 1999).

Peak Torque Maximum torque value achieved in the entire range of motion of a given movement (Perrin, 1993).

Resistance to Stretch Tendency of a limb to rotate in the opposite direction to a given movement as a result of tension within the tissues. Also referred to as the passive torque, measured in Newton metres (Nm), offered by the knee flexors during passive knee extension using a Kin/Com dynamometer. (Magnusson, 1998)

Range of Motion (ROM) Range through which a limb can move or rotate about a joint, measured in degrees (°) or radians (rads).

Stiffness Resistance of a structure to deformation, as determined by the slope of a Stress/strain curve (Woo et al, 1999). For studies in vivo, stiffness has been defined as the change in passive torque through a given range of motion, as determined by the slope of a Torque-Angle curve (Magnusson, 1998).

Stretch tolerance The maximum amount of muscle lengthening allowed by the subject without causing discomfort (Magnusson, 1998).

Torque A force that produces a tendency to rotate. Also referred to as a moment. Torque, in Newton metres (Nm), is the product of the magnitude of the force (N) and the perpendicular distance ($d\perp$), in metres, from the line of force through the axis of rotation, $T = F \times d\perp$ (Hall, 1999).

CHAPTER 2

Review of Related Literature

Introduction

This section will discuss topics related to this study. Topics discussed in this review include (1) the anatomy of the knee joint with emphasis on those structures that may provide passive resistance to knee extension, (2) a review of the protocols and reliability of the relevant tests of hamstring flexibility, (3) a discussion of the passive properties of skeletal muscle, (4) a review of different protocols for determining passive resistance to knee extension.

Anatomy of the Knee

The knee joint is a synovial joint complex consisting of three bones, the femur, tibia and patella, which articulate to form two joints, the tibiofemoral joint and the patellofemoral joint. The tibiofemoral joint is the articulation between the rounded distal femoral condyles and the relatively flat proximal tibial plateau. Because of the incongruency of the two joint surfaces, the knee joint relies on the surrounding ligamentous, cartilaginous, and musculotendinous structures for support. (Crouch, 1978)

Movements of the knee

The main motions that occur at the knee are flexion and extension in the sagittal plane about a left-right axis. This axis of rotation passes through the femoral condyles and changes position slightly as the joint moves through its range of motion. The knee moves through a range of about 140 degrees from full extension to full flexion. The articular surface movements of the femoral condyles on the tibial plateau are rolling and gliding. This combination of movements occurs as a result of the cruciate ligaments becoming taut during flexion and extension. Other movements that can occur at the knee joint are medial and lateral rotation in the transverse plane about a longitudinal axis. These movements are most prominent when the knee is in a position of 90 degrees of flexion. (Nordin & Frankel, 1989)

Ligaments of the Knee

The knee joint has four main ligaments associated with it to provide stability, two collateral ligaments and two cruciate ligaments (Figure 2-1). The medial collateral ligament is a broad, flat thickening of the joint capsule that connects the medial femoral condyle to the medial tibial condyle, with deeper fibres attaching to the medial meniscus (Crouch, 1978). It functions to protect the knee joint from valgus forces by resisting opening of the joint medially (Irrgang et al, 1996).

The lateral collateral ligament is a cord-like ligament that lies outside the joint capsule on the lateral side of the knee joint (Crouch, 1978). It attaches to the lateral femoral condyle proximally and the head of the fibula distally, and protects the knee against varus forces by resisting opening of the joint laterally (Crouch, 1978; Irrgang et al, 1996).

The two cruciate ligaments, the anterior cruciate ligament (ACL) and the posterior cruciate ligament (PCL), lie within the intercondylar notch of the femur inside the joint itself. The anterior cruciate ligament attaches to the anterior portion of the tibial intercondylar eminence and travels superiorly, posteriorly and laterally to attach to the medial aspect of the lateral femoral condyle (Moore, 1992). The ACL is composed of two bundles of fibres, the anteromedial bundle, which is under tension in flexion, and the posterolateral bundle, which is under tension in extension (Irrgang et al, 1996). The ACL is only under tension during the last 10 degrees of extension (Markolf et al, 1990). The ACL plays an important role in knee stability, preventing anterior shear of the tibia on the femoral condyles; as well, it resists rotational movements of the knee (Crouch, 1978). The ACL also resists hyperextension of the knee joint (Irrgang et al, 1996), with forces ranging from 50 N to 200 N in 5 degrees of hyperextension (Markolf et al, 1990). The PCL attaches to the posterior portion of the tibial intercondylar eminence and travels anteriorly and superiorly to attach to the lateral portion of the medial femoral condyle. It serves to prevent posterior translation of the tibia on the femur as well as resisting rotational movements of the joint. (Nordin & Frankel, 1989; Moore, 1992)

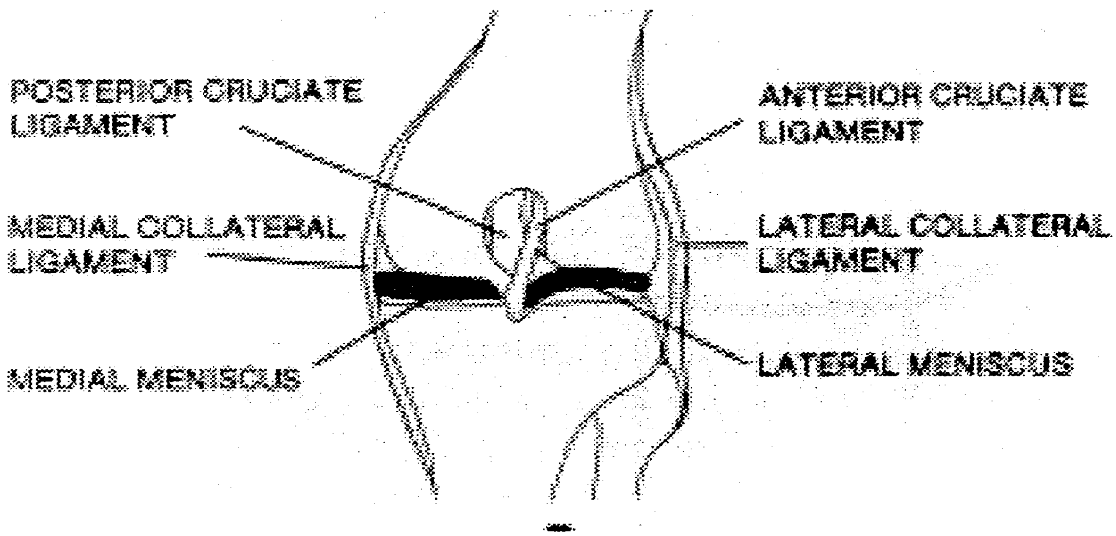


Figure 2-1: Anterior view of the structures of the knee, with the patella removed. (Nordin & Frankel, 1989)

Menisci

The medial and lateral menisci are semi-lunar, fibrocartilaginous discs that lie between the femur and the tibia (Figure 2-1). They provide stability to the tibiofemoral joint by making the tibial plateau more concave to better accommodate the femoral condyles. They also function in the absorption of shock and distribution of forces during weight bearing. (Moore, 1992; Irrgang et al, 1996)

Passive Resistance to Knee Extension

There are many tissues that cross the knee, both contractile and non-contractile. Structures that can resist passive knee extension include the anterior cruciate ligament, the posterior capsule of the knee joint, the sciatic nerve and related neural structures, the menisci of the knee, blood vessels, popliteus, gastrocnemius, plantaris, iliotibial band, biceps femoris, semitendinosus, semimembranosus, and connective tissue. Because it is not possible to determine the relative contribution of each of these tissues to the resistance of knee extension, they will be collectively referred to as the knee flexors.

Anatomy of the Knee Flexor Muscles

The main flexors of the knee are the hamstring muscle group, which are located on the posterior thigh (Figure 2-2). Included in the hamstring muscle group are the semitendinosus, semimembranosus, and the biceps femoris muscles. The semitendinosus originates on the medial aspect of the ischial tuberosity and inserts on the medial aspect of the proximal shaft of the tibia. The semimembranosus originates from the lateral portion of the ischial tuberosity and inserts on the posterior aspect of the medial tibial condyle. The biceps femoris muscle has two heads, the long head originating on the ischial tuberosity with the short head originating on the lateral side of the linea aspera of the femur. Both heads come together to insert on the head of the fibula. All three muscles are innervated by the sciatic nerve. Semitendinosus, semimembranosus, and the long head of biceps femoris are innervated by the L4, L5, & S1 nerve roots of the sciatic nerve and the short head of biceps femoris is innervated by the L5, S1, & S2 nerve roots. Semitendinosus and semimembranosus also produce medial rotation of the tibia on the femur, while biceps femoris can produce lateral rotation of the tibia on the femur. All three muscles cross the hip joint and, therefore, help to produce extension of the hip. Because all three muscles cross both the hip and knee joints, extension of the knee while the hip is in a flexed position results in stretching the hamstring muscles across two joints (Basmajian & DeLuca, 1985). The gastrocnemius muscle of the leg can also help flex the knee joint, as its two heads originate on the femoral condyles, although this capacity may be limited (Basmajian & DeLuca, 1985). Other muscles that have the ability to flex the knee include sartorius and gracilis, with their insertion on the medial tibial condyle as part of the pes anserine group, and the popliteus, as it crosses knee joint posteriorly. (Crouch, 1978; Moore, 1992)

Due to their ability to flex the knee joint, the hamstring muscles would also have the ability to produce passive resistance to knee extension. Basmajian and DeLuca (1985) suggested that the efficiency of the hamstrings as knee flexors increased when they are stretched by flexion of the hip. By this same rule, there would be an increase in the resistance to passive knee extension offered by the hamstrings with the thigh in a position of hip flexion. If these muscles were shortened, or stiff, or injured, their ability to produce resistance would be altered in that they would provide resistance earlier in the knee extension movement, thus decreasing the overall joint range of motion. In addition, the amount of resistance they would produce at the end range of motion would be decreased, thereby increasing the risk of strain injury. (Magnusson et al, 1997)

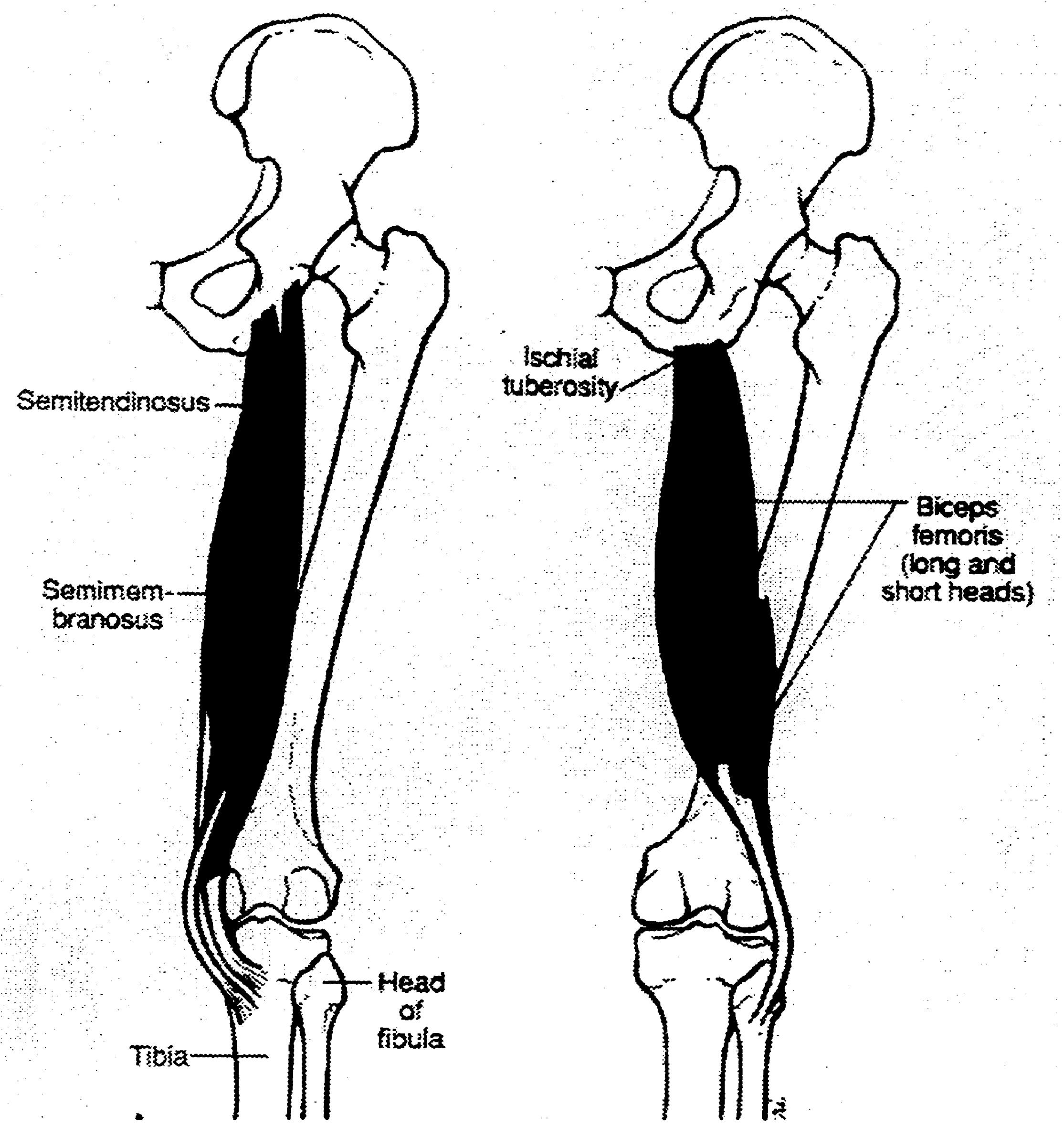


Figure 2-2: The muscles of the posterior thigh. (Moore, 1992)

Passive Properties of Skeletal Muscle

Introduction

It is important to examine the passive properties of skeletal muscle in order to understand the tissue response to lengthening, as this is directly related to the mechanism of muscle strain injuries (Garrett, 1996). This includes the responses to stretch under different conditions, such as different loading rates, warm-up, and previous injury. Many studies have been performed to investigate the properties of skeletal muscle. Initial studies were performed in vitro on animal (rabbit) skeletal muscle, allowing measurements of the muscle to be made directly. In the past decade passive properties of human skeletal muscle have been studied in vivo, with results compared to the previous in vitro studies.

Structure of skeletal muscle

Skeletal muscle is composed of both contractile and elastic components. Skeletal muscle is made up of long fibers of varying thickness and length that are surrounded by a loose connective tissue called the endomysium. These fibers are grouped into fascicles of various sizes that are surrounded by a dense sheath of connective tissue called the perimysium. Fascicles are grouped together to form a muscle which is further surrounded by the epimysium, a fibrous connective tissue. The collagen fibers of the epimysium and perimysium continue beyond the muscle fibers to form a tendon at each end of the muscle (Figure 2-3). The tendon itself is arranged in a similar manner, with collagen fibres grouped into bundles and surrounded by connective tissue.

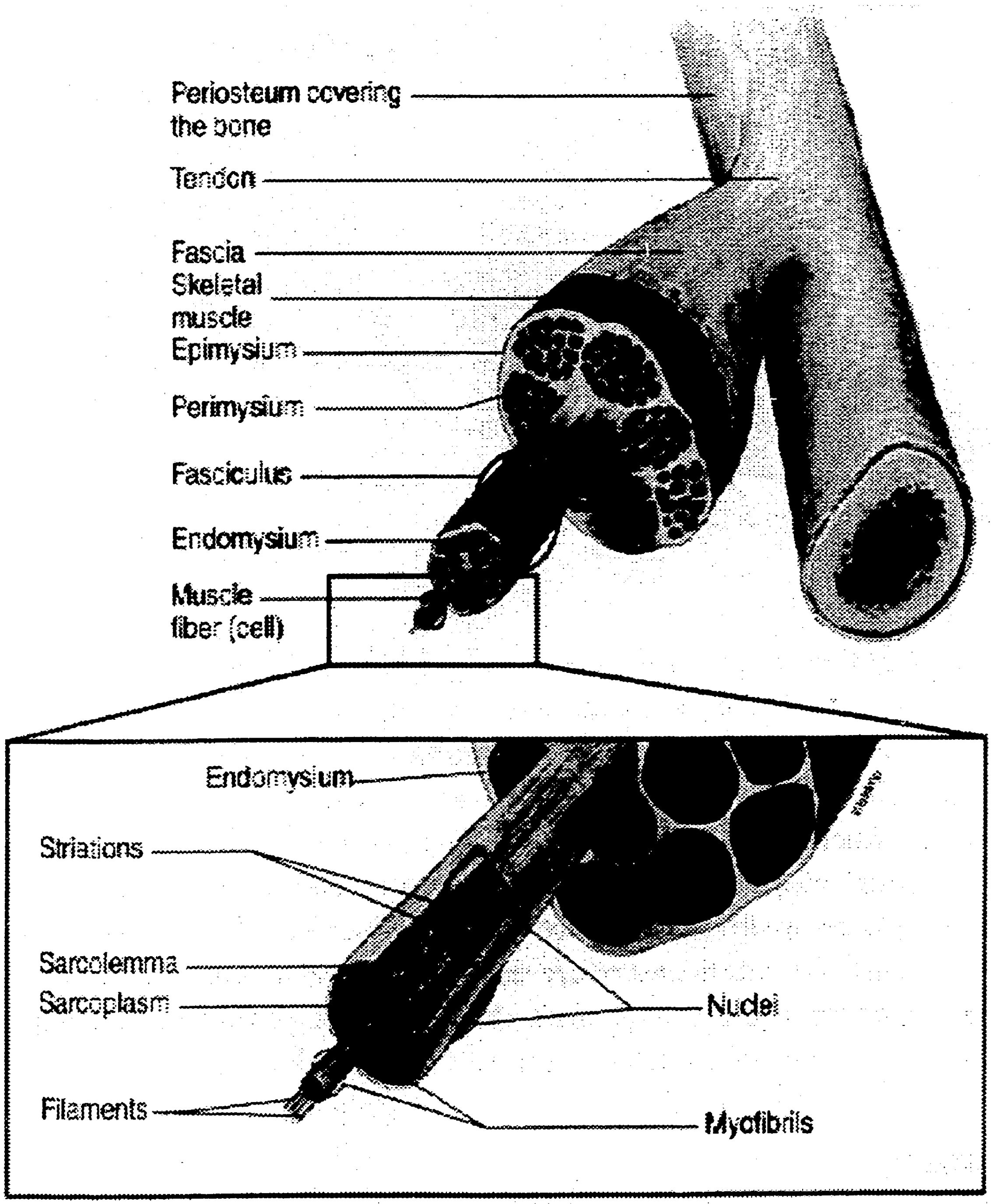


Figure 2-3: The structure of skeletal muscle. (Hall, 1999)

The tendons and connective tissue layers comprise the major elastic components of the muscle. They act both in series, represented by the collagen fibres in the tendons, and in parallel, represented by the epimysium, perimysium, and endomysium connective tissue layers within the muscle belly (Figure 2-4). As the muscle lengthens, the collagen fibres begin to straighten out and stretch providing resistance to lengthening, which can be measured under both in vitro and in vivo test conditions. (Nordin & Frankel, 1989)

The contractile component of the muscle, the actin and myosin filaments, also contribute to the passive resistance during muscle lengthening. During the non-contracted state of the muscle, there are a small number of actin-myosin cross-bridges that are connected. These bound cross-bridges function to resist short range lengthening of the muscle fibres (Cambell & Lakie, 1998), which provides a mechanical damping to lessen the effect of delayed neuromuscular reaction to movement and improve postural stability (Wang et al, 1993; Luo et al, 1994). The elastic contribution of the contractile component of the muscle fibres results from the bending of the myosin heads while they are attached to the actin filaments (Wang et al, 1993; Mutungi & Ranatunga, 1996; Uyeda et al, 1996; Campbell & Lakie, 1998).

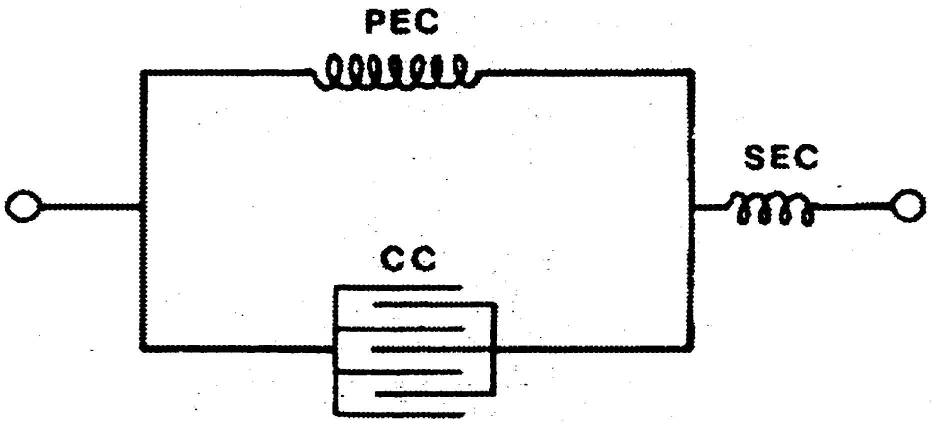


Figure 2-4: The series (SEC) and parallel (PEC) components of skeletal muscle. The series component represents collagen fibres in the tendons and the parallel component represents the collagen fibres of the connective tissue layers in the muscle belly. The contractile component (CC) represents the muscle fibres. (Nordin & Frankel, 1989)

Measurement of passive properties (in vitro & in vivo)

Studies measuring the passive properties of skeletal muscle in vitro have utilized the hind limb muscles, such as tibialis anterior and extensor digitorum longus, in anesthetized New Zealand white rabbits (Garrett et al, 1987; Strickler et al, 1990; Taylor et al, 1990; Noonan et al, 1993; Taylor et al, 1993; Mair et al, 1996). The muscles are separated from their distal attachments and placed in an Instron, which is a clamping device with a sensitive force transducer built in. With the hind limb stabilized, the muscles are pulled to failure under different loading rates and muscle conditions. The Instron determines the force involved in stretching the muscle to failure, as well as the length to which the muscle is pulled. This is important in determining the amount of stress a muscle can endure before injury or failure.

In vivo measurement of the passive properties of skeletal muscle have been determined using several different devices and stretch maneuvres. Passive tension was determined during a straight leg raise using an examiner-controlled load cell attached to a chain (McHugh et al, 1992; Halbertsma et al, 1999; Lee & Munn, 2000). In each study, the examiner passively lifted the leg with the load cell attached to the lower leg just proximal to the medial malleolus (Figure 2-5). A load cell device has also been employed (Mansour & Audu, 1986) to measure passive resistance to stretch during passive extension of the knee in different positions of hip flexion. This method provides a subjective measure of the passive resistance to stretch in that it depends on the examiner to produce tension in the load cell-chain device, as well as the determination of the end range of motion by the subject. The examiner is also required to maintain the load cell perpendicular to the leg in order to obtain accurate force measurements. Another potential source of error is the ability of the examiner to lift the leg at a relatively constant rate. This method could not be used if the examiner was physically unable to lift the limb, as in testing a professional football lineman for example.

Figure 2-5: Load cell on a chain set up. The load cell (3) is attached to the distal end of the test leg (2). (McHugh et al, 1992)

Resistance to stretch during passive knee extension has been measured with a dynamometer (Figure 2-6), such as a Kin/Com isokinetic dynamometer, in the passive mode of the device (Magnusson et al, 1995a; Magnusson et al, 1995b; Magnusson et al, 1996a; Magnusson et al, 1996b; Magnusson et al, 1996c; Magnusson et al, 1996d; Klinge et al, 1997; Magnusson et al, 1997; Magnusson et al, 1998; Magnusson et al, 2000a; & Magnusson et al, 2000b). The passive mode of the Kin/Com differs from the more common velocity mode in that there is no minimal force necessary to move the actuator arm. The Passive mode was designed as a means of performing repetitive, passive ROM exercises (Malone, 1988). The device could be programmed to move a limb in a set ROM, while the patient relaxed. The load cell attached to the actuator arm is still recording the forces associated with the movement during the passive mode, so the torque involved with the movement can determined by the dynamometer. The isokinetic dynamometer is the most common measurement tool of passive resistance of the knee flexors and has also been used to measure passive resistance in the plantar flexors (Lamontange et al, 1997).

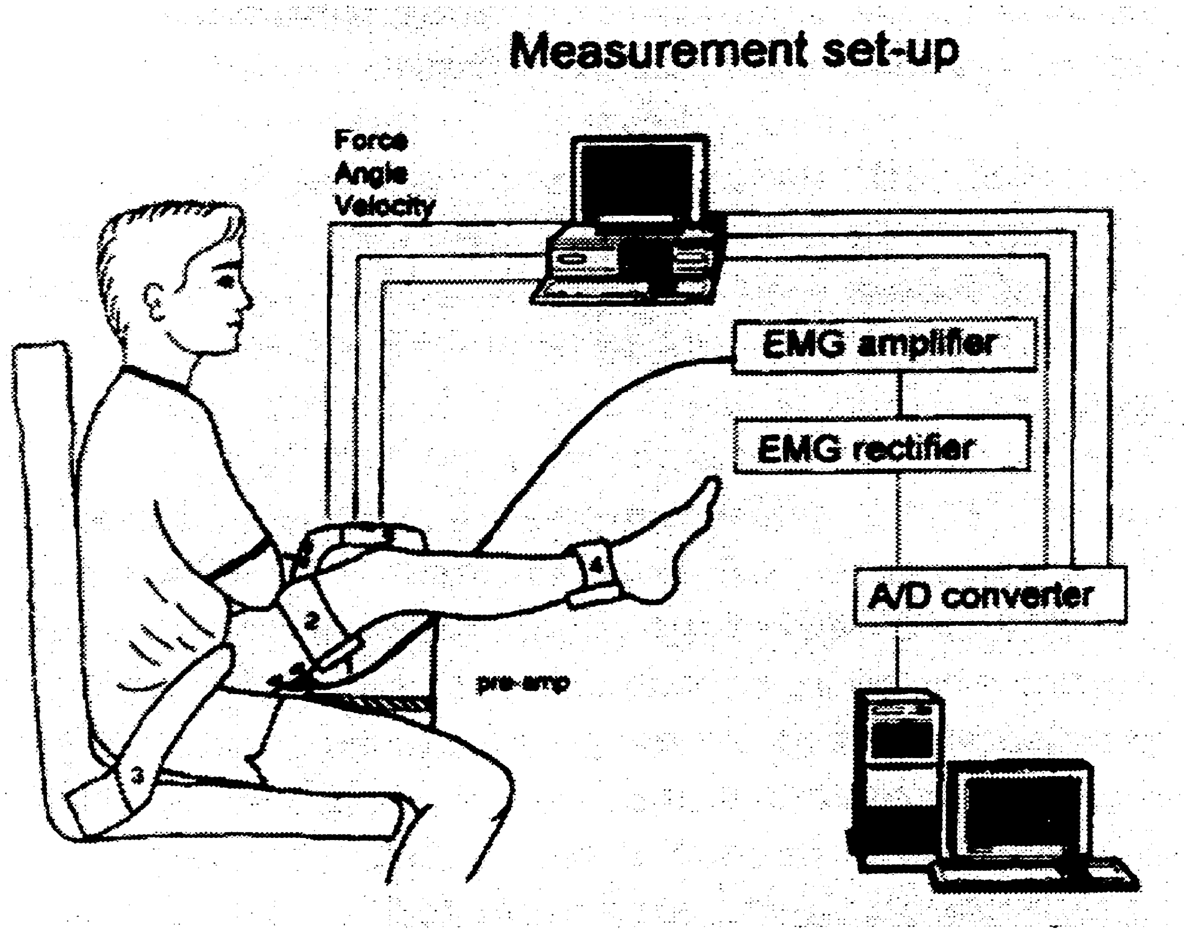


Figure 2-6: Passive dynamometer set up. (Magnusson, 1998)

Response to passive stretch

The behaviour of skeletal muscle tissue is said to be viscoelastic, meaning that it demonstrates both fluid-like and elastic properties in response to lengthening (Nordin & Frankel, 1989). The change in tensile forces of the muscle in response to elongation is non-linear. There are four characteristic regions of a load-deformation curve, as demonstrated by testing a rabbit tendon to failure (Figure 2-7). The first region is called the primary or toe region and represents tissue elongation with little increase in force as the collagen fibres begin to straighten out. The second region is called the secondary or linear region and is characterized by a rapid increase in stiffness as the straight collagen fibres stretch out. The third region is the end of the linear region when some of the collagen fibres begin to fail. As the fibres progressively fail, there are dips in the once linear curve. The fourth region of the load-deformation curve is the maximum load of the tissue, after which the collagen fibres fail rapidly and tissue completely ruptures. (Nordin & Frankel, 1989)

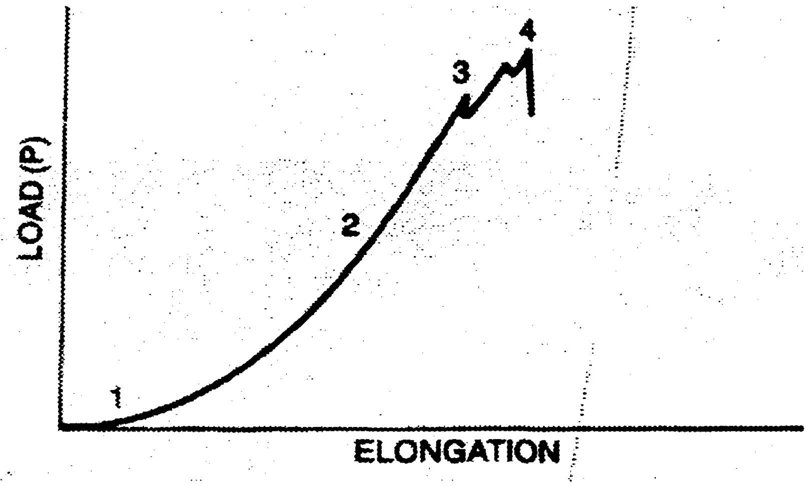


Figure 2-7: Load-deformation curve of skeletal muscle in vitro (Nordin & Frankel, 1989)

Skeletal muscle in vivo demonstrates the same toe-region and linear region (Figure 2-8) in response to stretch (Magnusson, 1998). When a limb is moved through a range of motion about a joint, the tissue being lengthened begins to provide passive resistance to that movement, denoted by the toe region of in Figure 2-8, in order to protect the joint from excess movement and potential injury. As the movement approaches the end range of motion, the amount of resistance offered by the elastic components of the muscle increases more rapidly, denoted in the linear region of the curve. The increase in resistance during slow passive stretch is not accompanied by an increase in EMG activity within the muscle, meaning that the activation level of the muscle is not changing, and thus, the resistance comes from the mechanical or elastic structures of the muscle (Magnusson et al, 1996d; Magnusson et al, 1997; McHugh et al, 1998).

The increase in the tension by the passive structures of the muscle during the stretch maneuver functions to restrict the joint movement and the lengthening of the muscle, providing a protective mechanism against strain injury.

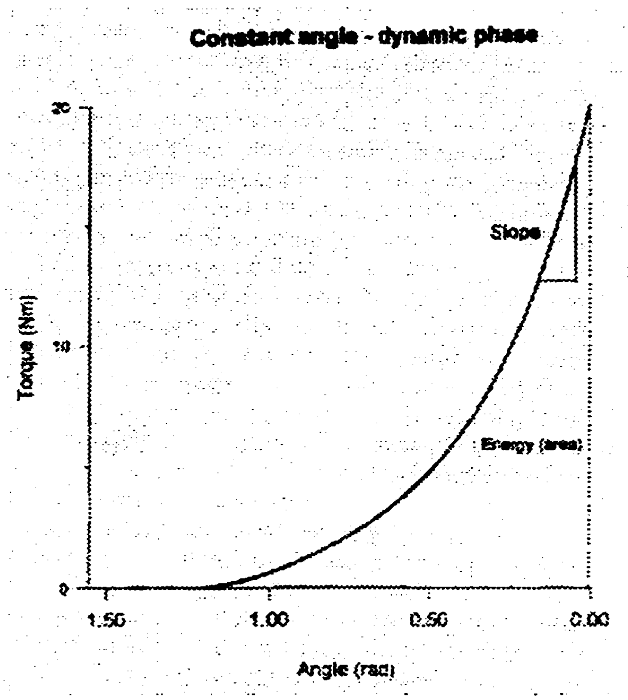


Figure 2-8: Torque-Angle curve from skeletal muscle in vivo (Magnusson, 1998).

The muscle-tendon unit also responds differently to changes in loading rate, exhibits creep, and demonstrates stress relaxation characteristics (Figure 2-9) (Taylor et al, 1990). Creep refers to the increase in length of tissue under a constant load while stress relaxation, or load relaxation, is defined as the decrease in tension within muscle tissue held at a constant length (Nordin & Frankel, 1989). In relation to the passive properties of skeletal muscle, the phenomenon of stress relaxation occurs as the collagen fibres in the muscle-tendon unit deform in adaptation to the new length. As a result of the lengthening, the amount of tension exhibited by the collagen fibres decreases. The creep phenomenon is exhibited as the collagen fibres stretch and deform in reaction to the load placed upon them. This phenomenon has not been demonstrated in vivo as it may result in a strain injury if the load is too high. This may have implications for stretching beyond the comfort level of a subject.

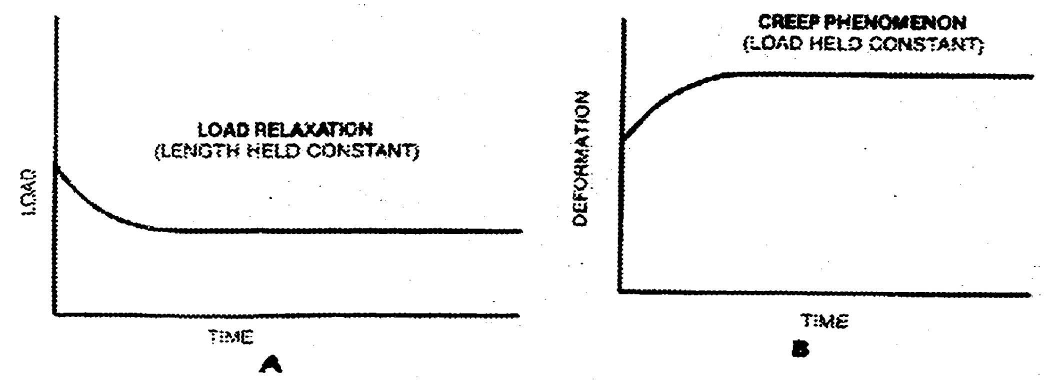


Figure 2-9: Stress (Load) relaxation and creep. (Nordin & Frankel, 1989)

In vivo studies of have demonstrated stress relaxation of muscle tensile force in response to a single static stretch. A study by McHugh et al (1992) demonstrated stress relaxation of human hamstring muscle in 15 healthy subjects during a passive straight leg test. The test involved a first static stretch to the maximum tolerated ROM, as measured by an electrogoniometer and second static stretch to a ROM that was 5 degrees lower than the first stretch. Each stretch was held for 45 seconds. The decreases in muscle tension during both stretches, as measured by a load cell attached to a chain, were significant, with percent decreases of $14.4 \pm 2.2\%$ and $13 \pm 2.3\%$ respectively. The authors concluded that the amount of stress relaxation was related to the amount of stretch placed on the tissue, but that the response was similar. The relaxation of muscle tensile force in vivo occurs when an athlete performs a static stretch of the hamstring muscles, such as a modified-hurdler's stretch. While the muscle is held at a constant length, the intensity of the stretch decreases as the tension in the tissue decreases over time.

A study by Magnusson et al (1996d) studied the response to stretch in the hamstring muscles of spinal cord-injured subjects with complete motor loss and healthy controls. Each subject performed a passive knee extension on a Kin/Com dynamometer at 5°/sec to a predetermined final ROM, where a stretch was held for 90 sec. EMG data in response to the stretch was recorded for each subject. Results showed that while there was a significant difference in the peak torque between the controls (34.2 ± 3.8 Nm) and the injured subjects (19.7 ± 5.0 Nm), there was no difference in the percent decrease in passive torque between groups (33% and 38%, respectively). The authors concluded because there was no measurable EMG response detected in either group during the stretch maneuver, the decline in the resistance to the static stretch was viscoelastic stress relaxation (Figure 2-10).

The results from the studies demonstrating stress relaxation show that the majority of the decrease in tension in the tissue occurs within the first 15-20 seconds of the static stretch maneuver. This is consistent with the findings of Taylor et al (1990), who noted that the most significant amounts of stress relaxation occurred during the initial 12 to 18 seconds of the stretch. This implies that static stretches should be held for at least that amount of time in order to be effective in relaxing the muscle-tendon unit.

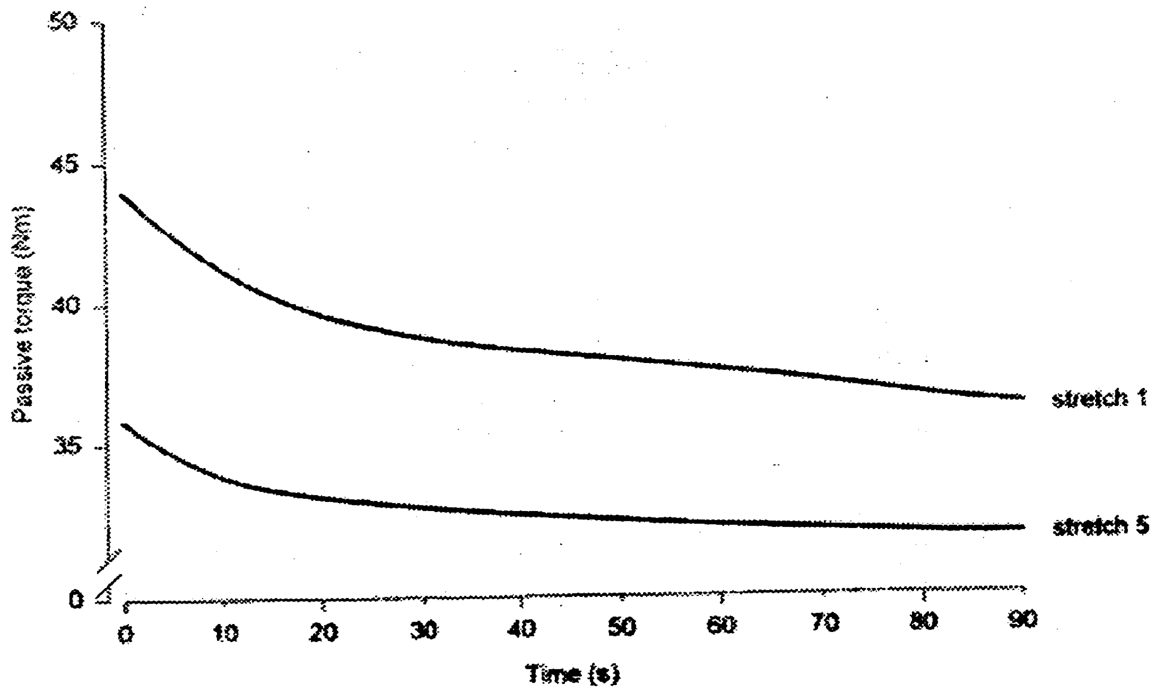


Figure 2-10: Stress relaxation during repeated static stretches in vivo (Magnusson et al, 1996b).

Effect of loading rate on passive muscle properties

Skeletal muscle responds differently to changes in rates of loading, showing more elastic properties as the rate of stretch increases. Taylor et al (1990) demonstrated this effect by stretching rabbit skeletal muscle failure in vitro at loading rates of 0.01 cm/sec, 0.1 cm/sec, 1 cm/sec, and 10 cm/sec. Results indicated that as the loading rate increased, there was a significant increase in the peak tensile force and the energy absorbed by the muscle-tendon units of both innervated and denervated tibialis anterior and extensor digitorum longus muscles. The passive muscle response to lengthening at higher joint angular velocities in vivo is a higher peak tension at shorter end ranges of motion. This means that movements involving high joint angular velocities, such as sprinting, create an increased stress within the tissue at shorter muscle lengths, which may increase the risk of strain injury. The rate-dependent response to stretch by skeletal muscle has implications in the safety of stretching techniques, suggesting that slow static stretching has a reduced risk for strain injury compared to ballistic stretching at a fast rate.

Effects of repeated stretching

Taylor et al (1990) showed the response of rabbit extensor digitorum longus muscle to ten repeated-stretches of 10% beyond original length at a loading rate of 2 cm/sec. There was a progressive decrease in the amount of tension with each stretch, with an overall decrease in peak torque of 16.6% from the first stretch to the tenth stretch, with most of this decrease in tension occurring between the first and fourth stretches. The authors suggested that the stretching history of the muscle-tendon unit is relevant and that stress relaxation leads to an internal change in structure of the specimen during each stretch. This may be a reason for including repeated stretching exercises in a warm-up protocol, with a minimum of four repeated stretches being necessary to bring about most of the lengthening of the muscle-tendon unit (Taylor et al, 1990).

A study by Magnusson et al (1996b) examined the response of human hamstring muscle to stretch in 13 uninjured subjects using a Kin/Com dynamometer and a repeated stretch protocol. The stretch maneuver involved a passive knee extension at 5°/sec to a predetermined final position, where it was held for 90 seconds. This was repeated 5 consecutive times, with a sixth stretch performed 1 hour later. Results showed significant decrease in stiffness, energy, peak torque (Figure 2-11), and stress relaxation between the first stretch and the fifth stretch, but no significant differences in these values between the first and sixth stretch. The authors concluded that a repeated stretch protocol causes a decrease in the viscoelastic properties of skeletal muscle, but that these changes return to baseline within one hour. These findings suggest that an optimal stretch protocol consists of stretches that are performed less than one hour before exercise, otherwise the effect of the stretch may wear off.

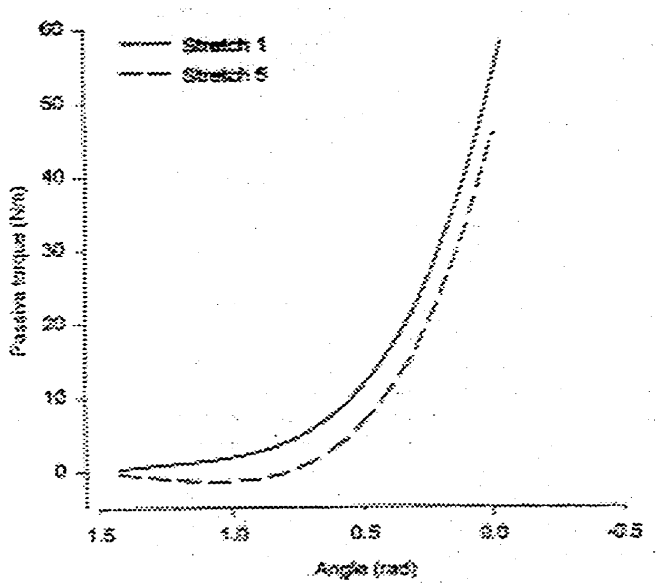


Figure 2-11: Differences in the peak torque during repeated stretches in vivo (Magnusson et al, 1996b)

A later study by Magnusson et al (1998) investigated the effects of repeated static and cyclical stretching on the viscoelastic properties of skeletal muscle in 12 recreational athletes. The resistance to stretch was measured using a Kin/Com dynamometer during three passive stretches of the hamstrings to the point of pain, 10 minutes apart. After the second stretch, each subject performed a 90-second static stretch and 10 cyclical stretches on the left and right side, respectively. For both interventions, there was a significant increase in the maximal joint angle and maximal stiffness (terminal 10° of maximal ROM) between all three stretches; however, the stiffness in a common range (terminal 10°ROM common to all 3 trials) was unchanged between stretches and sides. The authors concluded that a repeated static or cyclical stretching protocol has no effect on the viscoelastic properties of skeletal muscle, but that such protocols increase joint range of motion by increasing stretch tolerance.

Magnusson et al (2000a) also examined the effects of repeated static-stretches during exercise on the viscoelastic properties of skeletal muscle. Passive energy absorption was determined with a Kin/Com dynamometer before exercise (Preex), after 10 minutes of running (Postex10), and after 30 minutes of running (Postex30). Three stretch maneuvers were performed after the Postex10 test, with passive energy absorption measured during the stretches. The passive energy absorption was determined by calculating the area under the resultant Torque/Angle curves. Results showed that the energy absorption after stretch 3 (10.8 ± 1.8 J) was significantly lower than the Preex value (14.5 ± 1.7 J) and the Postex10 value (13.5 ± 1.9 J), but not the Postex30 value (13.3 ± 1.8 J). The Postex30 value was not different from the Preex and Postex10 values. The authors concluded that repeated static stretching has an immediate effect on passive energy absorption, but that this effect did not remain after 30 minutes of exercise.

Repeated static stretches have the effect of reducing the amount of passive tension within the muscle-tendon unit in the same range of motion, suggesting that an increase in range of motion would result from a repeated stretch protocol. This protocol should include a minimum of four static stretches, lasting 20 seconds each, and should be performed within the hour prior to exercise. In addition, the protocol should be performed during the exercise period in order to maintain the effects of the stretching.

Effects of stretching technique on passive muscle properties

It is a common belief in rehabilitation that stretching exercises, such as static and contract-relax stretching, increase the length of the tissue being stretched. Stretching programs most often result in improvements in joint range of motion. However, it is uncertain if these stretches actually increase the overall length of the tissue.

A study by Magnusson et al (1996a) examined the differences in passive torque, EMG activity, and stretch perception between a static stretch and a contract-relax (PNF) stretch of the hamstrings in 10 healthy subjects. Both a 10-second static stretch and the 6-second contract-relax stretch were employed at 10° below a pre-determined final angle. The knee was then extended either to the pre-determined final joint angle (constant angle protocol) or to a maximum joint angle determined by the onset of pain (variable angle protocol). Results indicated no difference in EMG activity or passive torque between the static or contract-relax stretch during the constant-angle protocol. However, during the variable-angle protocol, the contract-relax technique resulted in a greater passive torque and maximum joint angle than the static stretch, with similar EMG activity between methods. The authors concluded that the viscoelastic response to stretch was unaffected by the type of stretch maneuver, and therefore PNF stretching alters the perception of stretch.

It is evident that the evaluation of flexibility progress by range of motion values alone (i.e. via standard flexibility tests) may not be enough to judge muscle repair and rehabilitation. Athletes with previous hamstring strain injuries may still be predisposed to recurrent injury, even though they have attained a normal range of motion in a flexibility test.

Effects of strength training on passive muscle properties

It is generally agreed that strength training increases the contractile force output of skeletal muscle. However, the effect of strength training on the passive properties of skeletal muscle has not been examined until recently.

A study by Klinge et al (1997) examined the effect of isometric strength training with and without flexibility training on the viscoelastic response to stretch in twelve healthy subjects. Subjects performed isometric strengthening of both legs 3 times per week for 13 weeks, with stretching performed on one leg twice a day throughout the training period. Ten subjects served as controls, with no strengthening or stretching performed during the training period. Results indicated a similar increase in isometric strength of 43% on both legs. The peak torque, stiffness and energy absorbed increased significantly in both legs, however the stress relaxation response to static stretch (31-33%) was unaffected by the training. There was no significant difference in any of the measurements between limbs, suggesting that the flexibility exercises had no effect on the training responses. There were no changes in any measurements for the control group. This suggests that a strain-injury rehabilitation program that includes strengthening exercises will improve the ability of skeletal muscle to passively resist lengthening, by a possible mechanism of increased collagen fibre formation. This would result in a reduction of the risk of re-injury.

Effects of warm up on passive muscle properties

A number of in vitro studies have been performed looking at the effects of temperature on the passive properties of skeletal muscle. Noonan et al (1993) looked at the differences in the tensile behaviour of the rabbit tibialis anterior and extensor digitorum muscles at 25°C and 40°C. They noted among their findings that muscle at the colder temperature were stiffer and failed at higher loads than muscle at 40°C, but that the 40°C muscle had a larger total deformation at failure. Similar trends were found by Strickler et al (1990) using temperature differences of 35°C and 39°C. Noonan et al

(1993) also noted that the effects of temperature were also dependent on loading rate and contractile state, consistent with the viscoelastic properties of skeletal muscle.

Different results concerning the effect of temperature increase on the passive properties of skeletal muscle in vivo have been shown recently. A study by Magnusson et al (2000a) looked at the passive energy absorption of the hamstring muscle group in eight healthy subjects after different warm-up running protocols using a Kin/Com isokinetic dynamometer. Passive energy absorption was determined by calculating the area under the Passive Torque-Angle curve, measured in joules. Intramuscular temperature of the biceps femoris muscle was also measured before and after the warm-up exercise. Results indicated significant differences in intramuscular temperature before exercise (35.0 ± 0.4°C) and after 10 minutes (38.0 ± 0.2°C) and 30 minutes (38.8 ± 0.3°C) of running, but these increases had no measurable effect on the passive energy absorption of the muscle-tendon unit. The authors showed the possibility that the passive properties of skeletal muscle may not be affected by increases in intramuscular temperature in a physiological range.

Effects of previous injury on passive muscle properties

The effects of a previous injury on the passive properties of skeletal muscle have only been investigated with in vitro studies. Taylor et al (1993) studied the effect of previous strain injury on the tensile properties of muscle-tendon units. They stretched the extensor digitorum longus muscles in rabbits until they created a non-disruptive strain injury within the muscle. Failure properties and contractile forces were tested and compared to normal contralateral controls. Results indicated that the injured muscles had a peak load of 63% and an elongation to rupture of 79% of the values obtained with the control group muscles. There was also a decrease in the contractile force output of the injured muscles (20-33% decrease) as compared to the normal controls.

Nikolaous et al (1987) also studied the contractile ability of rabbit skeletal muscle following strain injury in a similar manner, but tested this ability over a period of seven days following injury. Their results showed that the contractile ability was decreased by 51% at 24 hours post-injury (max. decrease), and steadily increased to 92% after seven days, as compared to contralateral normal controls. This may have an effect on the ability of the musculature to actively prevent excessive joint ROM, thus increasing the risk of further injury.

Taylor et al (1993) concluded that the muscle-tendon units are more susceptible to injury following a strain injury than those of healthy muscle tissue because of the reduced ability to resist lengthening both actively and passively. However, studies on the passive properties of skeletal muscle with respect to previous strain injury have been limited to in vitro situations. It is necessary to examine the effect of muscle strain injury on the passive properties of skeletal muscle in vivo in order to improve rehabilitation methods and reduce the risk of re-injury.

Hamstring Flexibility Measurement

There are many tests used by clinicians to assess the flexibility of the hamstring muscle group. Among these are the Sit and Reach (SR) test, the Active Knee Extension (AKE) test, and the Passive Knee Extension (PKE) test. These three tests were selected for several reasons. The AKE and PKE tests were selected because they closely mimic the movement involved in the Passive Dynamometry test. The SR test was selected because it is a common field test of flexibility. In addition, comparison of these tests to passive dynamometry has not been well documented in the literature. This section will describe each of these tests and discuss related literature.

Sit and Reach Test

The sit and reach test is a common field test for assessing lower back and hamstring flexibility. Reports on the sit and reach test are abundant in the literature, with many tables of normal values with respect to age, gender, and activity level available (Shephard, 1991; Thorndyke, 1995; ACSM, 2000). The test is designed to measure trunk forward flexion, determining the range of motion of the hip, and the upper and lower back. The muscles stretched in the maneuver include the hamstrings and the erector spinae muscle groups, as well the triceps surae muscle group to a lesser degree (Thorndyke, 1995).

The sit and reach test is most commonly administered with the use of a standardized measuring box or similar device (Figure 2-12). The test is performed with the subject wearing loose clothing and in stocking or bare feet. The subject sits with his/her feet flat against the device and his/her knees extended. The upper limbs should be extended and the hands should overlap in a pronated position so that the middle fingers are even. The subject reaches forward slowly sliding both hands along the graduated measuring ruler of the device, exhaling as he/she flexes at the waist and hips. The knees should remain straight and the subject should be instructed not to bounce at any time (Figure 2-13). The best score of three trials is recorded at the final score (ACSM, 2000).

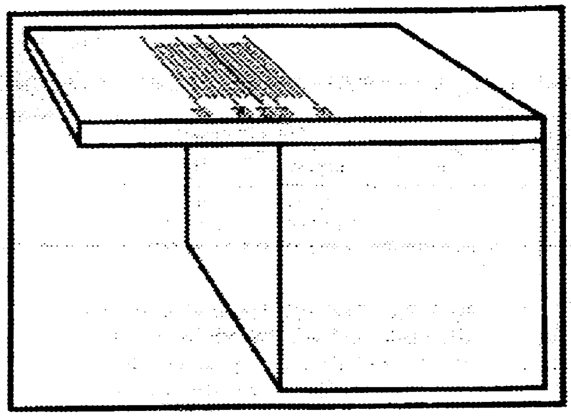


Figure 2-12: Box used in Sit and Reach Test (Cornbleet & Woolsey, 1996)

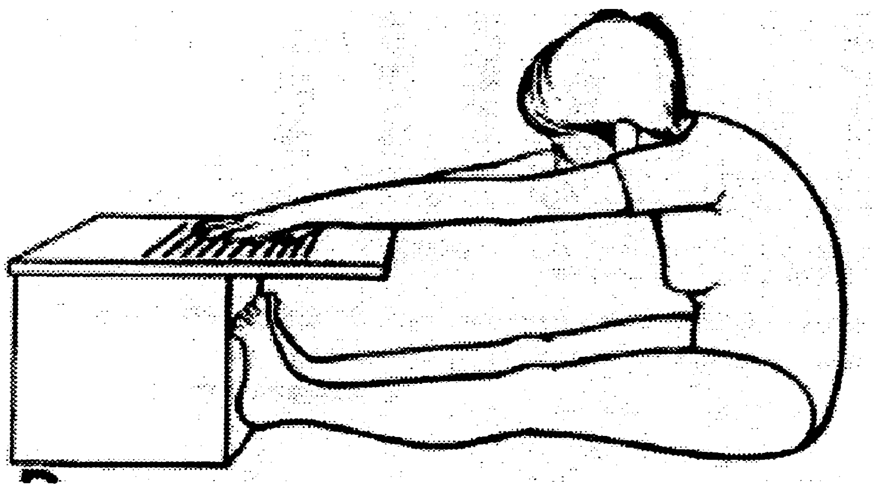


Figure 2-13: The Sit and Reach Test (Chang et al, 1988)

The reliability of the sit and reach test has been studied, with intraclass correlation coefficients as high as 0.99 (Jackson & Langford, 1989). The high reliability of the sit and reach test can be maintained by explaining the procedure thoroughly, using a standard sit and reach box and securing it against movement during the test, and through the reinforcement of correct technique with each trial (Thorndyke, 1995).

In a study evaluating the potential of overuse injury in runners, Hreljac et al (2000) found a significant difference in flexibility between previously injured and injury free runners. Subjects performed a standard sit and reach test, with the best of three trials taken as the final score. The injury free group scored significantly better than the group that had sustained a previous leg injury, with respective mean values of 3.2 ± 10.2 cm and -3.7 ± 11.5 cm. Measurements were made in centimetres beyond the soles of the feet (zero point), with negative values indicating the inability to reach the soles of the feet. The authors suggested that maintenance of hamstring flexibility might be an important factor in the prevention of overuse injuries in runners.

A study by Orchard et al (1997) compared muscle strength imbalances and flexibility with subsequent hamstring injury in Australian Rules footballers. Isokinetic testing was performed bilaterally at 60, 180, and 300 degrees/sec, with flexibility determined by the sit-and-reach test. Results indicated that the sit-and reach test did not correlate to hamstring injury.

A study by Chang et al (1988) compared the flexibility of power lifters with age-matched non-power lifters using the sit and reach test. Results indicated that the power lifters scored significantly better, with a mean value of 7.6 ± 4.0 cm beyond the feet, than their non-lifting peers, who scored a mean value of 0.8 ± 5.9 cm from their toes. The sit and reach test was the only flexibility test in the study in which the power lifters exceeded the scores of the control group. The other flexibility test performed was the behind the back reach test for shoulder flexibility.

Another study using the sit and reach test compared the flexibility of junior elite tennis players to the flexibility of junior athletes involved in other sports (Chandler et al, 1990). Results indicated that the sit and reach scores for the tennis players were significantly lower than the scores of the other athletes, 2.3 ± 8 cm and 6.2 ± 10 cm respectively, as measured in centimetres beyond the feet. The authors attributed this difference to a decrease in low back flexibility in the tennis group, as there were no significant differences in bilateral hamstring or gastrocnemius flexibility between groups, as measured by active straight leg raises and maximal foot dorsiflexion. This conclusion could be made because the Sit and Reach Test is a multi-joint flexibility test, stretching the tissues of the posterior leg as well as the trunk extensors. Tissues limiting SR test performance can be inferred by ruling out tightness in the other tissues using tests specific to those tissues.

A study by Cornbleet and Woolsey (1996) compared the flexibility of school-aged boys and girls using the sit and reach test with a measurement of the hip joint angle. The examiners utilized a standard sit and reach box, with the soles of the feet placed at the +25cm mark, allowing most subjects who cannot reach their feet to achieve a positive score. The hip joint angle was indirectly measured by placing the inclinometer on the sacrum while the subject was in the sit and reach position. The results indicated that the girls performed better than the boys on the sit and reach test, with respective mean values of 26 ± 7 cm and 22 ± 7 cm, and had a larger value of hip joint angle, with values of 85 ±

10 degrees and 75 ± 10 degrees (resp.). The authors suggested that the boys had shorter hamstring muscle group lengths than the girls.

A study by Jackson and Langford (1989) sought to determine the validity of the sit and reach test as a measure of hamstring and low back flexibility by comparison to a passive straight leg raise test and the measurement of lumbar spine flexibility in healthy adults. Lumbar spine flexibility was determined by measuring the increase in the distance between the L1 and S1 spinous processes during forward trunk flexion in a standing position. Flexibility measurements were made in a test-retest protocol in order to test the reliability of the methods. Results indicated that the sit and reach test is strongly related to hamstring flexibility ($r = .89$) and moderately related to low back flexibility in males, while it is only moderately related to hamstring flexibility in females. Test-retest comparisons showed that the sit and reach test was reliable, with an intraclass correlation of 0.99, as well as being a valid test of hamstring flexibility.

The sit and reach test is commonly used to assess flexibility, especially when testing large groups, because it takes little time and relatively easy to administer. Measurement devices used in the sit and reach test are easy to read and widely available. The test can even be administered with a ruler and some tape if a device is not available (ACSM, 2000). Weaknesses of the sit and reach test are that it does not account for anthropometric differences between subjects, such as arm and leg length, and it is a multi-joint test, which means that the test score does not necessarily reflect flexibility of the hamstring muscles alone.

Passive Knee Extension Test

The passive knee extension (PKE) test is considered a measure of the maximal length of the hamstring muscles and is thought to be a more selective alternative to the passive straight leg raise test (Gajdosik et al, 1993). The test is administered with the subject supine and the hip of the test leg flexed to 90 degrees (Figure 2-14). Most protocols have relied on the investigator to maintain the hip at 90 degrees of flexion (Worrell et al, 1991; Gajdosik et al, 1993; Bandy & Irion, 1994; Bandy et all, 1997; Bandy et al, 1998; Hartig & Henderson, 1999). However, the use of a chair (Handel et al, 1997) and the hands of the subject (Starring et al, 1988) to maintain hip angle have been reported. The examiner then passively lifts the leg, extending the subject's knee. The end point of the test has been documented as the researcher's perception of resistance to movement (Bandy et al, 1998; Hartig & Henderson, 1999), and as the point of discomfort or stretch tolerance as described by the subject (Starring et al, 1988; Gajdosik et al, 1993; Bandy & Irion, 1994; Bandy et al, 1997). The angle of the knee is measured at this point, most often with a goniometer. In most protocols the contralateral leg was kept straight at a 0° hip angle during passive extension (Gajdosik et al, 1993; Bandy & Irion, 1994; Bandy et al, 1997). However other researchers felt that partially flexing the contralateral limb at the hip and knee would help stabilize the pelvis (Starring et al, 1988). The use of a warm-up is not common, however, several static stretches are commonly used immediately prior to testing in order to reduce the effects of muscle lengthening from repeated trials during testing (Gajdosik et al, 1993).

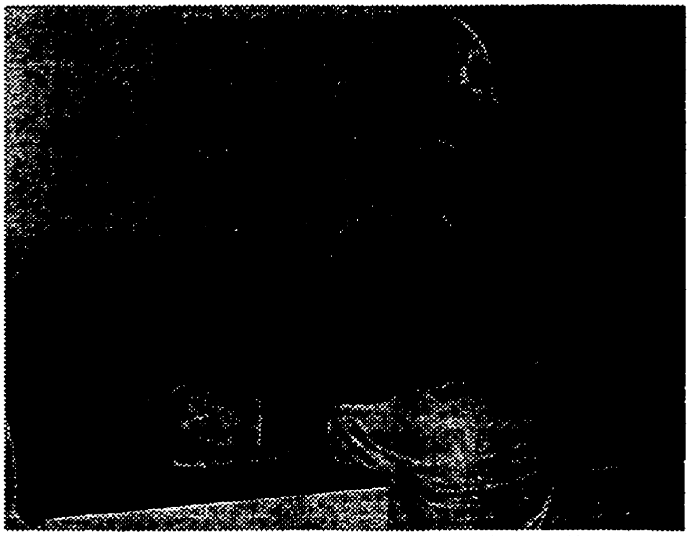


Figure 2-14: The Passive Knee Extension Test (Worrell et al, 1991)

A study by Worrell et al (1991) compared the strength and flexibility of injury free athletes with athletes who had sustained a non-contact hamstring injury that required at least 7 days away from their sport. Concentric and eccentric muscle torques for both quadriceps and hamstring muscle groups were assessed using a Kin/Com isokinetic dynamometer, while hamstring flexibility was assessed on both injured and non-injured extremities using the passive knee extension test and a goniometer. Results of the strength testing indicated no significant differences between groups. Flexibility test results showed significantly less range of motion for both extremities in the injured group as compared to the non-injured group, as well as significant differences between injured and non-injured extremities within the injured group. The authors stressed the importance of accurate assessment of flexibility of athletes with hamstring injuries during rehabilitation, and recommended periodic reassessment to ensure compliance with flexibility programs in order to prevent re-injury.

In a study by Hartig & Henderson (1999), the effect of a hamstring flexibility program on the rate of lower extremity injury in infantry basic trainees was investigated. Stretches were performed 3 times daily for 13 weeks in addition to a fitness program.

Passive knee extension test scores before commencement and after completion of the program were compared to those scores for a group that just performed the standard fitness program. All lower extremity injuries, including ligament sprains, muscular strains, and contusions, were recorded during the 13-week test period. Results showed a significant increase in hamstring flexibility in the intervention group, with a change in mean PKE test scores of 7 degrees. Injury incident rates were significantly different as well, with 16.7 % for the intervention group and 29.1% for the controls. The authors concluded that increased flexibility results in a decrease in the number of lower extremity injuries.

Bandy et al (1998) used the passive knee extension test to measure the effect of static stretch and dynamic range of motion training on hamstring flexibility. In pre- and post-test measurement sessions, the researcher passively extended the subject's knee, with the hip at 90° flexion, to a point at which the researcher perceived a resistance to movement. Results indicated significant improvements in hamstring flexibility in the static stretch and dynamic range of motion groups as compared to controls (11.42 ± 6.52 degrees and 4.27 ± 2.67 degrees, respectively). The authors concluded that the static stretching protocol was better than the dynamic range of motion protocol, but both would result in an increase in hamstring flexibility.

Another study by Bandy et al (1997) used the passive knee extension test to measure the effect of different parameters of time and frequency of a static stretch protocol on the flexibility of the hamstring muscles. The passive knee extension angle was measured with a goniometer. Results of the six-week program showed that all stretch groups significantly increased their PKE test scores by about 10 degrees (range of

10.05 to 11.50 degrees) when compared to the controls that did not stretch. However, there were no significant differences between groups indicating that increasing stretch duration beyond 30 seconds or increasing stretch frequency does not result in greater hamstring flexibility. This confirmed results of a previous study by Bandy & Irion (1994), which reported that sustaining stretches for 30 seconds was better than stretching for 15 seconds or no stretching, and that holding stretches for longer than 30 seconds did not produce additional increases in flexibility.

In a study by Starring et al (1988), the passive knee extension test was used to compare the effect of sustained passive and cyclic stretching on the resting length of the hamstring muscles. Results of the cyclic stretching and the sustained stretching to maximal tolerance showed significant increases in passive knee extension of 15.4 ± 4.97 degrees and 13.4 ± 4.38 degrees, respectively, after 5 consecutive days of stretching. The authors concluded that either protocol is effective in creating substantial increases in hamstring flexibility, as measured by the passive knee extension test.

The passive knee extension test is a reliable test for measuring the passive range of motion of the knee. This test mimics the movement performed during testing with a dynamometer in the passive mode. One limitation of the passive knee extension test is the subjective nature of the end-point determination, in that it depends on both the perception of resistance to movement by the therapist and the stretch tolerance of the subject. Also, the use of an external device to maintain hip joint angle is not widely reported.

Active Knee Extension Test

The active knee extension test has been documented in the literature as an alternative to the active straight leg raise (Gajdosik & Lusin, 1983; Cameron & Bohannon, 1993). The test is performed with the subject lying supine on a mat, board or plinth (Figure 2-15). The subject actively extends the knee of the test leg while the leg is held at a hip flexion angle of 90 degrees. The subject is aided in maintaining the angle at the hip by keeping the thigh in contact with a bar, frame, or cradle (Figure 2-16).

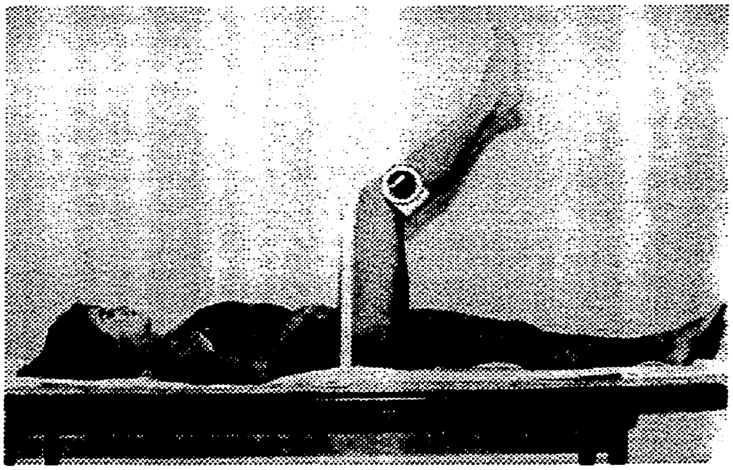


Figure 2-15: The Active Knee Extension Test (Sullivan et al, 1992)

Figure 2-16: The use of a cradle in the active knee extension test (Bruce, 1989).

The non-test leg is most often left extended on the test surface, but can be flexed if a cradle device is employed (Bruce, 1989). The pelvis and the thigh of the non-test leg are usually strapped to prevent extraneous movement (Gajdosik & Lusin, 1983; Cameron & Bohannon, 1993), but have been left unstabilized (Sullivan et al, 1992; Webright et al, 1997). The initial protocol (Gajdosik & Lusin, 1983) required the subject to extend his/her knee until his/her leg began to shake. This is termed myoclonus, which is a reflex-firing action of the muscle being stretched in an effort to protect the tissue from injury. The subject was then instructed to slightly flex his/her knee until the myoclonus stopped, which was considered to be the end point of the maneuver. Subjects stated that they no longer felt a stretch sensation at this end point. Later studies (Bruce, 1989; Sullivan et al, 1992; Cameron & Bohannon, 1993; Worrell et al, 1994; Webright et al, 1997) ignored the myoclonus effect and determined the end range to be the point at which the knee could no longer be extended without the stretch sensation remaining comfortable. Knee joint angle may be determined using a goniometer (Gajdosik & Lusin, 1983), a flexometer/inclinometer attached to the lower leg (Bruce, 1989; Sullivan et al, 1992; Worrell et al, 1994), or by videotape or photographic analysis (Cameron & Bohannon, 1993; Webright et al, 1997). Four practice trials are commonly performed prior to the actual test trials in order to decrease the potential for increases in knee joint angle that may result from repeated measures from a cold start (Webright et al, 1997). The test may be a measure of the initial length of the hamstring musculotendinous unit (Gajdosik et al, 1993).

A study by Gajdosik and Lusin (1983) sought to determine the reliability of the active knee extension test. Fifteen healthy subjects performed the test on two separate occasions, as per a test-retest format. Reliability coefficients were .99 for both the right and left extremities. The authors concluded that the high reliability was due to strict body stabilization methods, accurate instrument placement, and a well-defined end point of motion. Other measures of reliability have been reported, with intraclass coefficients ranging from 0.93 to 0.99 (Sullivan et al, 1992; Cameron & Bohannon, 1993; Worrell et al, 1994).

A study by Cameron and Bohannon (1993) compared hamstring flexibility measurements between the active straight leg raise (ASLR) and the active knee extension (AKE) tests. Twenty-three subjects performed two trials of each test, with two minutes rest between trials and tests. Results showed a significant correlation between the two tests ($r = -0.718$; $p < 0.001$). The authors concluded that both tests provide an indication of the same phenomenon, presumably the length of the hamstring musculotendinous unit, and thus the active knee extension test was a reliable alternative to the active straight leg test.

In a study by Sullivan et al (1992), the effect of different stretching techniques on hamstring flexibility was measured using the active knee extension test. Subjects with limited hamstring flexibility performed eight sessions of either static (SS) or contract-relax-contract (CRC) stretch maneuvres in either an anterior or posterior pelvic tilt position over a two-week period. Active knee extension measurements were made using a flexometer/inclinometer attached to the lower leg and were taken at the commencement and the end of the two-week period. Results indicated a significant increase in flexibility in the groups performing the SS and CRC stretches in the anterior pelvic tilt position, 9.2 degrees and 12.9 degrees, respectively. The authors recommend using the anterior pelvic tilt position when performing either stretching technique, as this position may place a greater force on the musculotendinous unit and therefore increase the length of the hamstrings more efficiently.

Another study by Worrell et al (1994) used the active knee extension test to determine the most effective method of increasing hamstring muscle length. The effect of an increased muscle length on isokinetic peak torque as measured by a Biodex isokinetic dynamometer was also determined. Nineteen healthy subjects performed 15 sessions of either static or contract-relax-contract stretches in an anterior pelvic tilt position over a three-week period. Flexibility and strength measures were determined at the beginning and at the end of the three-week period. Increases in flexibility for both protocols were not significant ($p = 0.082$), nor were there any significant differences between the two stretching protocols. Knee flexor peak torque increased significantly at

60 and 120°/sec eccentrically and at 60°/ sec concentrically (8.5%, 13.5%, and 11.2%, respectively). The authors concluded that an increase in flexibility produces an increase in selective isokinetic peak torques and that the active knee extension test has a high intratester reliability (ICC = 0.93).

Webright et al (1997) used the active knee extension test to study the effect of a nonballistic active knee extension stretching technique on the flexibility of the hamstrings, and compared it to a static stretching protocol. Stretches were performed in 84 sessions over a six-week period. The authors concluded that a program of nonballistic, repetitive active knee extension exercises results in an increase in hamstring flexibility of 10.2%, but the increase is not different from that achieved using a static stretching program (8.9%).

A study by Bruce (1989) utilized a modified active knee extension test to measure differences in hamstring injured and non-injured subjects in order to determine factors implicated in hamstring strain injuries. The modification to the test procedure was the use of a cradle to maintain the hip at a flexion angle of approximately 90 degrees. There were no significant differences in hamstring flexibility measurement between injured and noninjured limbs within or between groups. The author felt that the use of the cradle to maintain hip position allowed the subject to concentrate on the knee extension movement without having to actively stabilize the hip.

The active knee extension test is an effective measure of active joint range of motion and has been associated with the active range of motion of different sporting activities (Hahn et al, 1999), but it does have several limitations. Cameron & Bohannon (1993) stated that the test is only useful if the subject cannot fully extend their knee when their hip is in 90 degrees of flexion. The flexibility of subjects who can fully extend their knee in this position will not be accurately assessed, as they may not feel a stretch in this position. Another limitation is the necessity of an external device to keep the hip flexion angle consistent, which may not be practical in a clinical setting. Additionally, the end point of the movement is subject to the stretch tolerance of the subject and control of the myoclonic reflex.

Passive Dynamometry Testing

The use of an isokinetic dynamometer to measure the resistance to passive joint motion has become quite common in the last decade. With respect to the knee, there are several different methods employed to test resistance to knee flexion and extension.

The majority of the studies on the passive resistance to knee extension have been performed by Magnusson and colleagues (1995a, 1995b, 1996a, 1996b, 1996c, 1996d, 1997, 1998, 2000a, 2000b) using a Kin/Com isokinetic dynamometer at the Sports Medicine Research Unit of the Bispebjerg Hospital in Copenhagen, Denmark. The method used is a modification of a seated dynamometer protocol (Figure 2-17). The backrest is placed in a vertical position and the thigh of the test leg is raised 30-45 degrees above the level of the seat. This position of hip flexion, accompanied by ankle plantar flexion, is an attempt to isolate the hamstring myotendinous unit as the predominant resistors to knee extension. Because the knee never approaches full extension in this test position, the potential resistance offered by the posterior knee capsule is considered to be minimal. With the ankle in a position of plantarflexion, the potential contribution of the gastrocnemius muscle group can also be reduced. The knee is flexed to 70 degrees below horizontal and passively moved at 5°/sec to a pre-determined end point. The end point is determined as the maximum range of knee extension that elicits a strong but not uncomfortable stretch sensation in the posterior thigh, similar to the sensation felt during a static stretch maneuver. The end position is often held to measure the viscoelastic response to the stretch placed on the knee flexors.

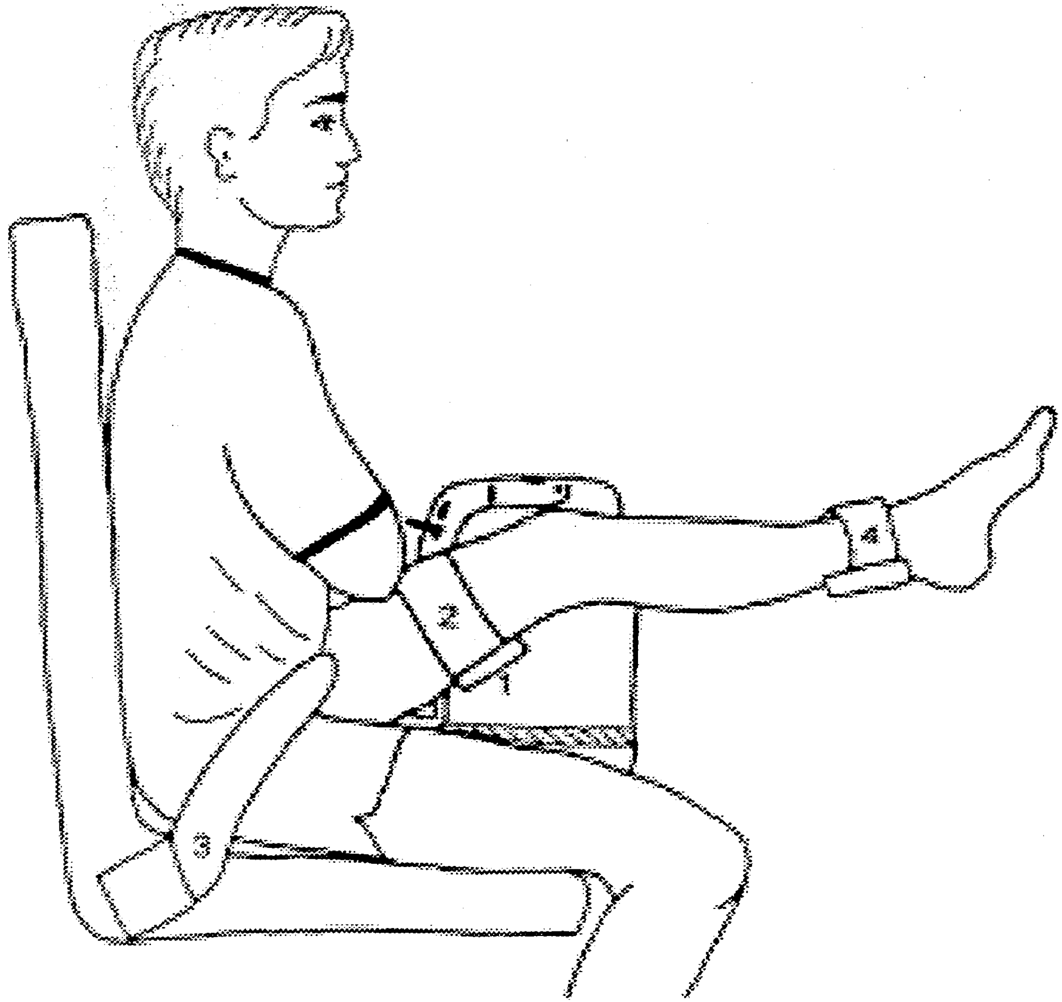


Figure 2-17: **Setup for passive dynamometry testing (Magnusson et al, 1995a)**

Gravity-corrected values of passive torque are measured throughout the range of the movement. The range of motion of the movement is measured in radians, with 0 rads corresponding to the leg at horizontal, which allows variables such as energy to be reported. Variables such as peak torque and stiffness of the tissue are most often reported from the resulting torque measurements, which are discussed in subsequent sections. Other variables that may be reported are final torque following static stretch, change in torque during static stretch, and energy absorbed by the tissue during the dynamic stretch. The energy absorbed by the tissue, in joules, is calculated by the measuring the area under the Torque-Angle curve. Values for energy absorbed have been reported as 14.5 +/- 1.7 J (Magnusson et al, 2000b) and 18.6 +/- 3.1 J (Magnusson et al, 1996b).

Another method of passive resistance to knee flexion employs a similar procedure to the passive knee extension test, with the subject lying supine and the hip stabilized in a position of 90 degrees of flexion (Strauss, 2000). A trunk-stabilizing vacuum splint is used to minimize the movements of the trunk and head. The knee is passively extended at an angular velocity of 5°/second from horizontal to a pre-determined end point. Different stretching and range of motion protocols can be used. One limitation of this method, similar to the passive knee extension test, is that the subject being tested must not have enough flexibility to reach full extension in this position, as ligamentous and capsular tissue become taut near full extension and will likely contribute to passive resistance to the movement.

A Kin/Com isokinetic dynamometer was used in a case study by Ainslie & Beard (1996) to quantify the resistance of the knee extensors to passive knee flexion in a 28 year old, male footballer with a chronic hamstring injury. Variables measured by the dynamometer included the joint angle and range of motion, in degrees of flexion from anatomical position, and the passive torque of the knee extensors in resistance to knee flexion, reported in Newton metres. The subject rested on the dynamometer table in a prone position and the knee was flexed with the hip in anatomical position. The results indicated that the increase in passive resistance to knee flexion occurred earlier in the injured leg when compared to the uninjured leg. The authors stated that this was a preliminary article designed to introduce the use of dynamometry for measurement of passive resistance in the quadriceps musculature and that further study was required to validate the method and demonstrate reliability.

Passive Peak Torque

Passive peak torque is the most commonly reported variable with respect to passive knee extension testing. The passive peak torque value occurs at the end range of the knee extension movement and is the highest recorded torque value during a passive test. The end range of the knee extension test is commonly determined as the maximum knee extension without the subject experiencing discomfort (Magnusson et al, 1995a, Magnusson et al, 1996; Magnusson et al, 1996b; Magnusson, 1998). This position is subjective in that it depends on the subject's perceived comfort during a passive stretch maneuver.

Magnusson et al (1995a) reported a mean passive peak torque value of 44.0 ± 3.9 Nm for 10 normal subjects using a Kin/Com isokinetic dynamometer. These were similar to the mean passive peak torque value of 42.8 ± 3.7 Nm, as reported by Magnusson et al (1996b) in a study of 13 uninjured subjects using a Kin/Com dynamometer. Another study by Magnusson et al (1996a) reported a mean passive peak torque value of 48.9 ± 4.1 Nm in a study of ten male recreational athletes using a Kin/Com dynamometer. In a study comparing endurance athletes with normal and tight hamstrings, as determined by a toe-touch test, Magnusson et al (1997) reported mean passive peak torque values of 31.6 ± 4.1 Nm and 15.4 ± 1.8 Nm respectively. The authors used a Kin/Com dynamometer to assess passive resistance to knee extension.

Stiffness

Stiffness of the tissue, as calculated by the slope of the Torque-Angle curve, has been reported in many studies. The stiffness represents the resistance of the tissue to passive stretch in the final range of the movement. Magnusson et al (1995a) reported a mean stiffness value of 30.2 ± 3.2 Nm/rad for 10 normal subjects using a Kin/Com isokinetic dynamometer. A similar study by Magnusson et al (1996b) reported a mean stiffness of 47.7 ± 4.2 within the final range of muscle lengthening, during testing of 13 normal subjects with a Kin/Com dynamometer. In a study comparing endurance-trained athletes with tight hamstrings to those with normal hamstring flexibility, Magnusson and colleagues (1997) reported mean stiffness values of 28.0 ± 2.9 Nm/rad and 54.9 ± 6.5 Nm respectively.

Stabilization

Stabilization of the subject is widely used in maximal isokinetic testing (Perrin, 1993). A study performed by Magnusson et al (1993) examined the effect of four different stabilization methods, ranging from full stabilization to minimal stabilization, on maximal knee flexor and extensor torque production in 20 subjects. Results indicated that the method of stabilization significantly affected the maximal torque output achieved, with the greatest torque produced during maximal stabilization, with the leg, thigh, pelvis and trunk stabilized to the actuator arm, seat, and backrest, respectively. These results did not agree with those found by Hanten & Ranberg (1988), who reported no significant differences in the maximal torque values between maximal and minimal stabilization methods, although a backrest was used in both test situations. The use of secure subject stabilization is recommended for all isokinetic testing (Perrin, 1993).

The use of a backrest and secure strapping around the pelvis, distal thigh, and distal leg in passive dynamometer protocols is well documented (Magnusson et al, 1995a; Magnusson et al, 1995b; Magnusson et al, 1996a; Magnusson et al, 1996b; Klinge et al, 1997; Magnusson et al, 1997; Magnusson et al, 1998b; Magnusson et al, 2000a; Strauss, 2000). The subjects were also instructed to cross their arms in front of their chest in these protocols to promote relaxation and prevent extraneous movement of the upper body. Magnusson et al (1995a) stated that the use of adequate subject stabilization during passive dynamometer testing was necessary to ensure reliability and reproducibility of results, with similar conclusions noted in later studies (Magnusson et al, 1996b, Nuyens et al, 2000).

Gravity Compensation

Many authors have noted errors in the moment values obtained for the knee flexors and extensors due to the moment of the weight of the leg. In a seated testing position, this moment would have the effect of increasing the measured knee flexor moment because the weight of the leg would cause a moment in the same direction. The opposite effect would be seen with respect to the knee extensor moment as the knee extensors must overcome the moment due to the weight of the leg. The measured knee extensor moment would then be lower than its actual value. The effect of the moment of the weight of the leg increases as it moves closer to a horizontal position (Figure 2-18).

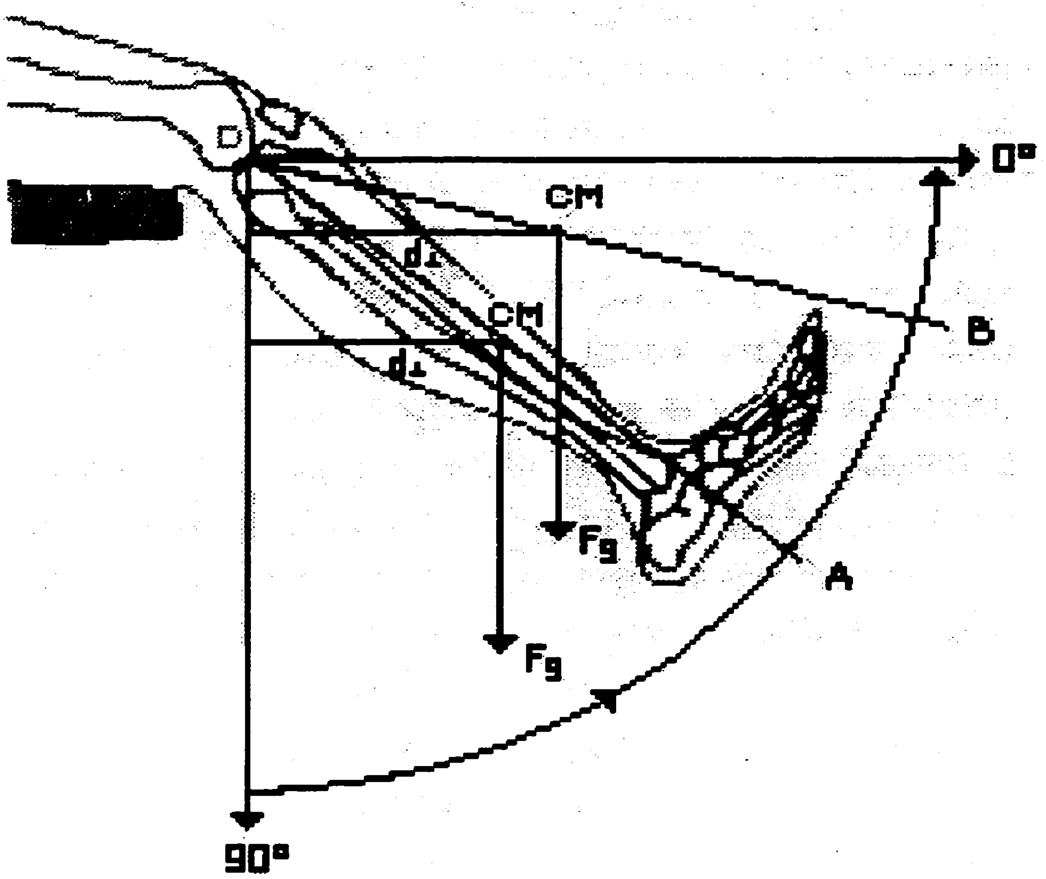


Figure 2-18: Moment of the weight of the leg. The moment would be greater with the leg at position B than at A, as the moment arm is greater. The force due to gravity would remain the same. (Adapted from Baltzopoulos & Brodie, 1989)

There have been several methods of correcting for the moment due to the weight of the leg used in past studies (Herzog, 1988; McHugh et al, 1992; Magnusson et al, 1995a; Kellis & Baltzopoulos, 1996). The authors stressed the importance of using gravity correction in the determination of the resultant joint moment from the moment recorded by the dynamometer software.

A study by Kellis & Baltzopoulos (1996) compared the effectiveness of different methods of gravity compensation on a Biodex dynamometer. The methods compared included static measurement of the leg by the dynamometer in a seated and a supine position, estimation the leg moment from anthropometric measurements, and the direct measure of the moment using a reaction board. Results indicated that the moments of the weight of the leg as measured by the dynamometer were significantly different than those obtained using anthropometric data and the reaction board method. The authors concluded that the most accurate method of gravity compensation was using anthropometric measurements, as they were not affected by muscle action factors.

Reliability of the Kinetic Communicator Isokinetic System

Several studies have assessed the reliability and validity of the Kinetic Communicator exercise device (Farrell & Richards, 1986; Hanten & Lang, 1988; Mayhew et al, 1994). A study by Farrell & Richards (1986) examined the reliability and validity of the Kin/Com with regards to the testing and measurement of the function of joints in the human body. The examiners focussed their evaluation on the lever arm position, lever arm angular velocity, and load-cell force measurement systems, considered to be the primary functions of the device. These functions were tested under both static and dynamic conditions, with measurements made using external devices and compared to those simultaneously made by the Kin/Com system. The authors concluded that the Kin/Com unit tested succeeded in producing valid and reliable measurements of the conditions of the strain gauge and lever arm apparatus.

In a similar study by Mayhew et al (1994), the reliability and validity of measurements of force, angle and velocity by a Kin/Com dynamometer were assessed. These measurements were compared to an external measuring device with known weights, angles and velocities. Results indicated that the intraclass correlation coefficients for all test conditions and measurements were above 0.99. The authors concluded that the measurements made by the Kin/Com dynamometer are accurate and able to be replicated.

Hanten & Lang (1988) investigated the reliability and validity of the measurements of torque, work, and power by the Kin/Com isokinetic dynamometer using certified weights and external measuring devices. Results also indicated intraclass correlation coefficients of 0.99 or greater for all static and dynamic test conditions. It was concluded that the Kin/Com is able to provide valid and reliable measurements of torque, work, and power and should continue to be used in the assessment of patients or subjects.

With respect to passive movements, the reliability of the Kin/Com has been examined by Magnusson and colleagues (1995a, 1996b) using the previously described protocol in a test-retest format. Intraclass correlation coefficients ranged from 0.91 to 0.99, with respect to measurements of peak torque, final torque, stiffness, and energy absorbed. The authors attributed the high reliability to adequate and secure stabilization, and clear, consistent instructions.

CHAPTER 3

Methods and Procedures

Introduction

The purpose of this study was to determine the relationship between the measures of flexibility obtained from the SR, AKE, and PKE tests, and the peak torque, angle at peak torque, stiffness values obtained during passive knee extension on the Kin/Com isokinetic dynamometer. The study also examined the differences in flexibility measurement scores between individuals with a previous hamstring strain and individuals with no history of hamstring pathology. The hypothesis was that there would be no correlation between the measures obtained from the SR, AKE, and PKE tests, and the measures obtained during passive knee extension on the Kin/Com isokinetic dynamometer. Secondarily, there would be no difference in these outcome measures between normal individuals and individuals with a history of hamstring strain injury.

Ethics approval for this study was received from the University of Manitoba Education/Nursing Research Ethics Review Board prior to data collection.

Subjects

Subjects consisted of 20 healthy male athletes between the ages of 18 and 28 (mean age = 22.0 years). The subjects were competitive athletes, participating in varsity track and/or varsity football. These sports were chosen because they involve sprinting maneuvers that have been associated with hamstring strain injury (Worrell et al, 1991; Devlin, 2000). The subjects were recruited by personal communication with the researcher and by posters at various locations at The University of Manitoba. Those subjects who were willing to participate were placed in either the control group or experimental group, based upon history of injury. Subjects in the control group (N=10) consisted of those athletes that had no history of hamstring injury and were free of leg pathology at the time of testing. Subjects in the experimental group (N=10) were those athletes that had suffered a unilateral hamstring injury requiring time away from their sport within the 18 months prior to testing. They were actively participating in their sport without symptoms and were free of lower limb pathology at the time of testing.

Subjects were given an informed consent form and a written description of the test procedure. The consent form included the guarantee of confidentiality as well as the assurance of the right to withdraw from the study at any time. Each subject was required to sign the informed consent form to confirm that he had read and understood the testing procedures and their rights as a participant. Subjects were asked to dress in loose shorts for their test session.

Apparatus

Materials to be used during testing included a stopwatch, a pair of anthropometric calipers, a cradle and strapping for knee extension testing, a Panasonic Omnimovie SVHS video camera with video tape, a 27" Panasonic colour television, a Panasonic Omnivision SVHS video cassette recorder with jog-shuttle capabilities, a Flex Test Sit and Reach device (Lafayette Instrument Co., Lafayette, Indiana), and a Kin/Com isokinetic dynamometer (Model # 500-9) with computer and printer.

Protocol

Upon arrival at the Biomechanics Lab at the University of Manitoba, each subject read and signed the Adult Informed Consent form (Appendix A). Each subject then filled out an information sheet and completed a Hamstring Injury Questionnaire (Appendix D).

Prior to commencement of testing, the subject's anthropometric variables (height, weight, and thigh & leg lengths) were measured and the subjects performed the pre-stretching exercise. All subjects performed all tests on both limbs, with each test completed on one limb, followed by the other. The order of the tests rotated for each successive subject in each group. Subjects were randomly assigned an order of testing and starting limb when they arrived for their test session.

Hamstring Injury Questionnaire

Each subject completed an Injury questionnaire (Appendix D) prior to testing in order to give the examiner details about the subject's training habits, hamstring injury history, and current sport(s) involvement. Information regarding limb dominance (preferred limb) and involvement in a regular strength and/or flexibility program was obtained. Previously injured subjects supplied information about which leg was injured, the time away from full activity, and history of previous injury.

Anthropometric measurement

After explanation of the testing procedure and the signing of the informed consent form, and completion of the questionnaire, the subject's mass, in kilograms, was determined using a balance scale and their height, in metres, was measured using a wall scale. The length of the subject's thigh, in metres, was determined by measuring the distance between the greater trochanter of the femur and the lateral femoral condyle. The length of each subject's leg, in metres, was also determined by measuring the distance between the lateral femoral condyle and the distal tip of the lateral malleolus of the fibula using a pair of standard anthropometric calipers.

Pre-Stretching

Prior to testing, each subject performed 5 static hamstring stretches, in the form of toe touches, with each stretch held for 30 seconds. This was performed to minimize the effect of an increase in stretch tolerance and, therefore, range of motion found during the first four stretch maneuvers (Taylor et al, 1990). This pre-stretching protocol had been performed in previous studies (Gajdosik et al, 1993; Webright et al, 1997).

Videotaping Setup

The video camera (Panasonic Omnimovie SVHS) was placed approximately 4 metres away from the test cradle in order to film the sagittal plane view of the active and passive knee extension tests. The size of the subject in the viewer was as large as possible, while still capturing the entire range of motion of the leg. Small silver markers were placed on the following anatomical landmarks: the greater trochanter of the femur, the lateral femoral condyle, and the lateral malleolus of the fibula. These landmarks corresponded to the thigh and leg segments as well as the axis of rotation of the knee joint, and were used for determination of knee joint angle. The sagittal plane view for each test trial was videotaped so that the knee joint angle could be determined by subsequent video analysis.

Sit and Reach Test

The sit and reach test was administered with the use of the Flex Test Model 01175 (Lafayette Instrument Co., Lafayette, Indiana), a standardized Sit and Reach device (Figure 3-1). The test was performed with the subject wearing loose clothing and stocking or bare feet. The subject sat with his feet flat against the device and his knees extended. The arms were extended with the wrists pronated and the hands overlapping so that the middle fingers were even. The subject slowly reached forward, sliding both hands along the measuring ruler of the apparatus and exhaling as he flexed at the waist and hips, until he could reach no further. The subject was instructed to keep his knees straight and not to bounce at any time. The average of the closest two trials was recorded at the final score.

Figure 3-1: The Sit and Reach Test.

Active Knee Extension Test

The active knee extension exercise was performed in a cradle designed to hold the subject's thigh in a relaxed position at approximately 90 degrees of hip flexion. The cradle was similar to that used by Bruce (1989). The test leg was secured to the seat of the cradle by a Velcro strap placed around the distal thigh. The subject was instructed to hold onto the sides of the cradle in order to maintain the hip angle at 90 degrees by keeping the pelvis in contact with the device. The subject was also instructed to close his eyes to eliminate visual perception of the movement. From a starting position of approximately 90 degrees of knee flexion, the subject was instructed to slowly extend his knee to the point at which he could not extend further without being uncomfortable. This was the end point of the maneuver, which was consistent with the end point used in previous studies (Bruce, 1989; Sullivan et al, 1992; Cameron & Bohannon, 1993; Worrell et al, 1994; Webright et al, 1997). The subject paused briefly with the leg at the end point to ensure capture of the position on video before returning the leg to the start position.

Four practice trials were performed in a range well short of maximal extension allow movement familiarization prior to the actual test (Webright et al, 1997). The subject then performed three, maximal range of motion test trials, with a rest between trials lasting a few seconds. The average of the two closest trial scores was taken as the final score.

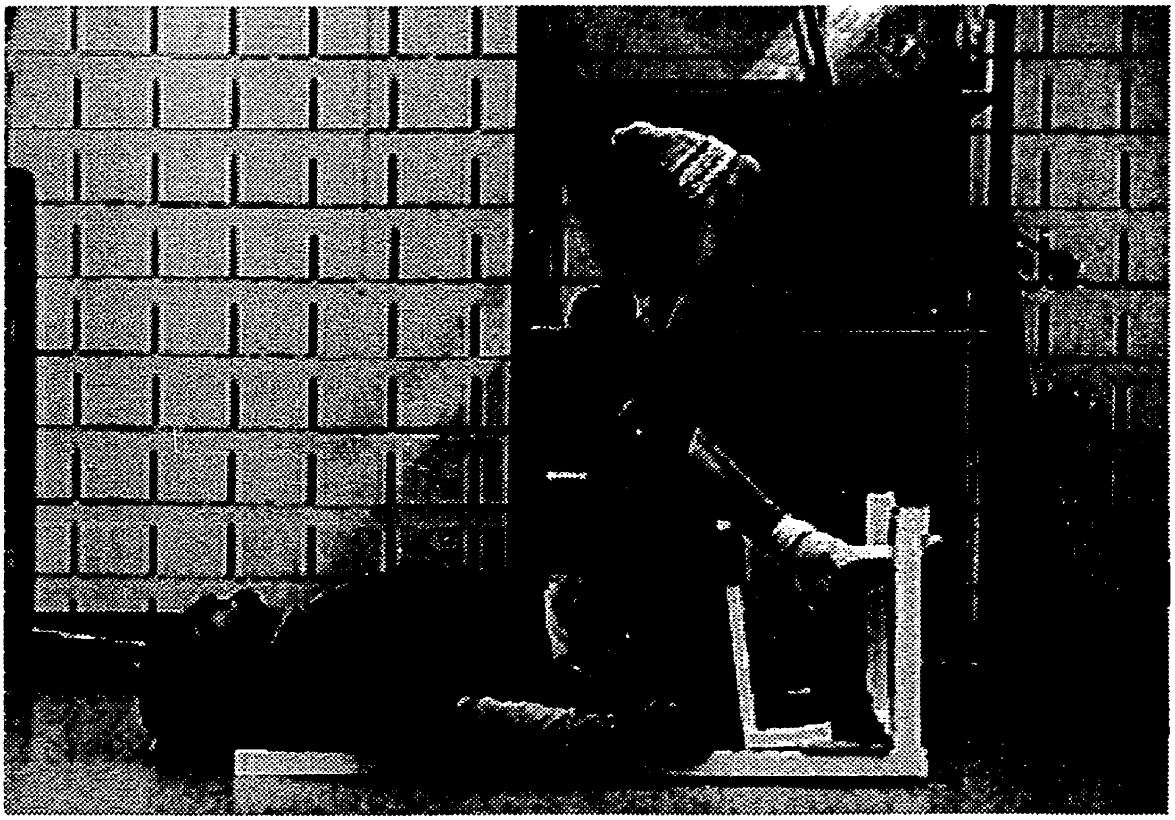


Figure 3-2: Cradle and subject position during the Active Knee Extension Test.

Passive Knee Extension Test

The subject was asked to lie with the leg supported in the cradle in the same manner as described in the Active Knee Extension test, with the same strapping method around the distal thigh employed (Figure 3-3). Again, small silver markers were placed on the greater trochanter of the femur, the lateral femoral condyle, and the lateral malleolus of the fibula. The subject was asked to relax his leg and close his eyes, as he held onto the sides of the cradle in order to maintain the hip angle at approximately 90 degrees. Starting in a position of approximately 90 degrees of knee flexion, the examiner passively extended the subject's knee until the subject stated that his knee could no longer be extended without being uncomfortable. This was the end point of the movement, which was consistent with the end point used in previous studies (Starring et al, 1988; Gajdosik et al, 1993; Bandy & Irion, 1994; Bandy et al, 1997). The knee was held at the end point briefly to ensure video capture of the position, before being passively returned to the starting position.

Four practice trials were performed in a range well short of maximal extension to allow the subject to become familiar with the movement prior to the actual test trials (Starring et al, 1988). Three maximal range of motion test trials were then performed, with a rest between trials lasting a few seconds. The average of the two closest trial scores was taken as the final score.

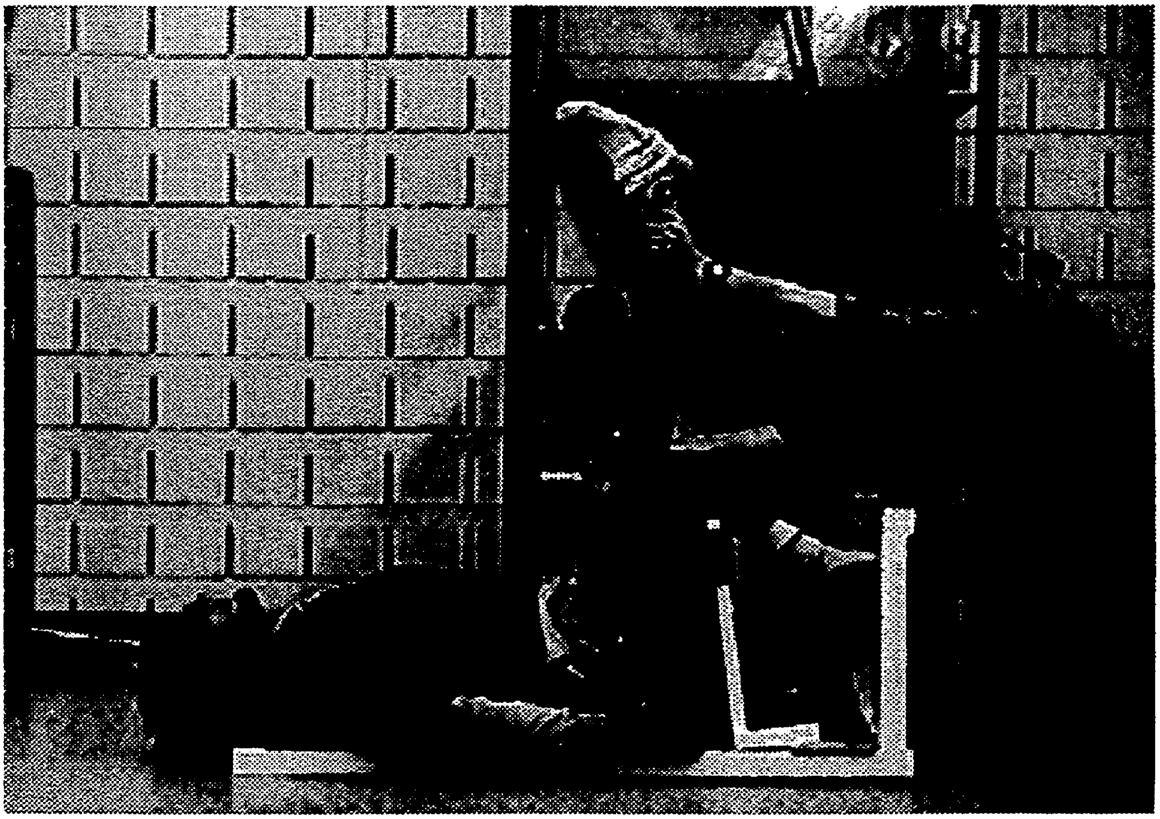


Figure 3-3 The Passive Knee Extension Test.

Passive Kin/Com Dynamometer Test

The subject was positioned on the seat of the Kin/Com with his back against the backrest (Figure 3-4). Due to the backward slope of the Kin/Com backrest, a modified thigh pad was placed under the distal thigh that raised the thigh approximately 15 degrees above the horizontal in order to maintain the hip at approximately 90 degrees of flexion. The same modified thigh pad was used for all subjects. The distal thigh was secured to the thigh pad and the seat with a Velcro strap and the pelvis was secured with a seat belt mounted to the seat/backrest. The subject was also instructed to cross his arms in front of his chest. The Kin/Com table and head height were adjusted to align the axis of rotation of the actuator arm with the lateral femoral condyle. The Kin/Com arm radius was adjusted so that the distal edge of the resistance pad was 2 centimetres above the medial malleolus of the tibia, and the leg was secured to the load cell with a strap. The actuator arm radius was entered into the terminal for automatic torque calculation by the computer.

With the leg starting in a vertical position, corresponding to a knee joint flexion angle of approximately 105 degrees, the examiner slowly moved the leg and actuator arm, and extended the knee until the subject stated that the leg could no longer be extended without being comfortable. This position represented the end point of the movement, which is consistent with the end point used in previous studies (Magnusson et al, 1995a; Magnusson et al, 1995b; Magnusson et al, 1996a; Magnusson et al, 1996b). The subject experienced a stretch sensation in the posterior thigh similar to that of a static stretch maneuver. The end point position was entered into the Kin/Com computer control interface and the leg was immediately returned to a position below the end point. Care was taken so as not to provoke a painful response in the determination of the end point (Magnusson et al, 1995a).

The leg and the actuator arm were placed in the starting position and the test trial began. The subject was asked to close his eyes during the test. He was also instructed to relax as much as possible and not offer any voluntary resistance to the movement. The dynamometer passively moved the leg at 5°/second toward the pre-determined end point. Once the end point was reached, the actuator arm paused briefly for 0.5 seconds, after which it returned the leg to the starting position at an angular velocity of 10°/second. There was a short pause, lasting 0.5 seconds, between successive trials. This was a limitation of the passive mode of the Kin/Com software, as the pause at the end ranges of motion (start and end point) had to be the same.

The subject was allowed four practice trials from the starting position to a range well short of the end point, to promote familiarization with the movement. The actual test consisted of three trials in the maximum range. The computer detected the angle of leg and the force from the load cell through out the test trial at a sampling rate of 100 Hz. The computer automatically calculated the torque output for each sample using the actuator arm radius as previously entered. The torque values, along with the corresponding actuator arm angle were saved on disk for subsequent analysis.

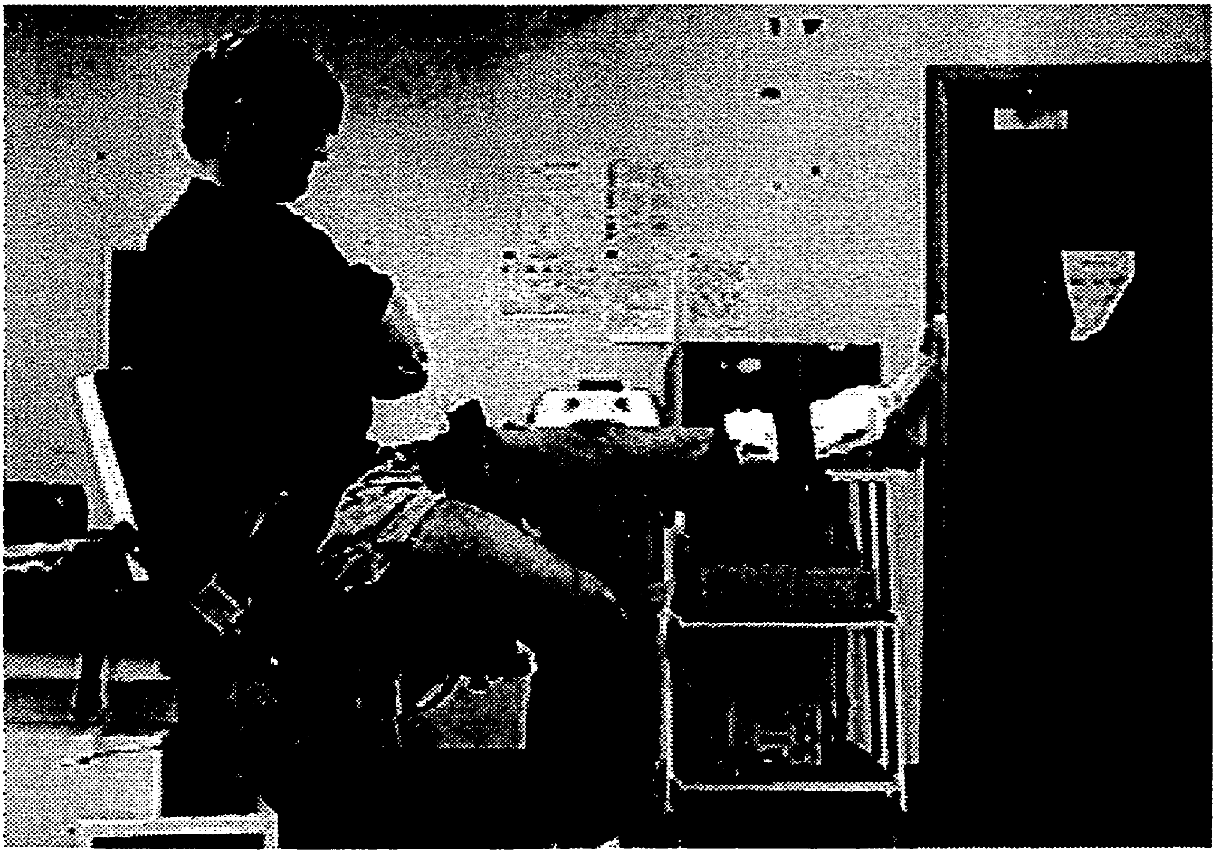


Figure 3-4. Set up for the Kin/Com Isokinetic Dynamometer Test.

Data Analysis

The AKE and PKE tests were videotaped in the sagittal plane view and the angle of the knee joint was determined during subsequent video analysis. Small silver markers were placed on the following anatomical landmarks: the greater trochanter of the femur, the lateral femoral condyle, and the lateral malleolus of the fibula. These landmarks corresponded to the thigh and leg segments, as well as to the approximate axis of rotation of the knee joint (Nordin & Frankel, 1989), and were used for determination of knee joint angle. After testing was completed, the video frame showing the end-point of each test was determined and displayed on the television using the jog-shuttle feature on the VCR. The position of the centre of the hip, knee, and ankle joint markers were traced onto a transparency using a fine tip permanent marker. A stick-figure model of the leg was made, with the thigh, axis of rotation, and leg represented by the hip-knee segment, knee joint marker, and knee-ankle segments, respectively. Using a protractor, the angle of the knee joint was then determined by measuring the degrees from anatomical position of the leg relative to the thigh. This method was used by Webright et al (1997) and reported an intratester ICC of 0.98 and a standard error measurement of 1.69 degrees. The angle from full extension, to the nearest degree, was taken as the score for that trial. The knee joint angle at anatomical position, with the knee fully extended, was denoted as 0° of flexion. The average of the two closest trials was taken as the final score for that test.

The passive torque and joint angle data from the dynamometer, sampled at a rate of 100 Hz, were transferred to a Microsoft Excel™ file on a personal computer for analysis (Appendix B). A limitation of the software for the Kin/Com Model #500-9 was that the angle of the actuator arm was reported to the nearest degree, even though the actuator arm was still moving through that degree. At slower angular velocities, such as the 5 deg/sec employed for this study and other studies (Magnusson, 1998), there were approximately 20 different passive torque values reported for the same angle.

In order to obtain a single sample to represent each angle, every 20th sample, starting with the 5th sample, was recorded throughout the entire range. By starting on the 5th sample, the recorded passive torque value for each angle was taken from about the middle of the values reported for that angle. This method was employed during pilot testing and seemed to be successful. The same method was used for all trials and all subjects. The average of the torque values at each angle for the three trials was used as the dynamometer moment (M_D) for that angle.

Corrections for the moment of the weight of the leg were made in the Excel file. The moment of the weight of the leg was determined from anthropometric measurements made prior to testing, as recommended by Kellis & Baltzopoulos (1996), and was calculated by the equation:

$$\mathbf{M} = \mathbf{F} \times \mathbf{d}\perp$$
$$\mathbf{M_W} = \mathbf{(0.06 \times BWt) \times (0.437 \times l \cos\theta)}$$

Where,
M_W = moment due to the weight of the leg, in Newton metres,
0.06 = the ratio of the weight of the leg, relative to total body weight,
BWt = body weight, in Newtons, as calculated by the product of the mass (kg) and the acceleration due to gravity (g), wt = mg.
0.437 = ratio of the distance of the CM from the proximal joint and the total segment length,
$l \cos\theta$ = length of the leg, in metres, multiplied by the cosine of the angle (θ) of the leg, relative to the horizontal ($\cos\theta$).

This represented the perpendicular distance from the vertical line of force of the weight of the leg, acting through the CM, to the axis of rotation (Figure 3-2). The effect of the angle-cosine relationship was that when the leg was horizontal, M_W was maximal (cos 0 = 1), and when the leg was flexed to 90 degrees (vertical), the effect of M_W was absent (cos 90 = 0). (Kellis & Baltzopoulos, 1996)

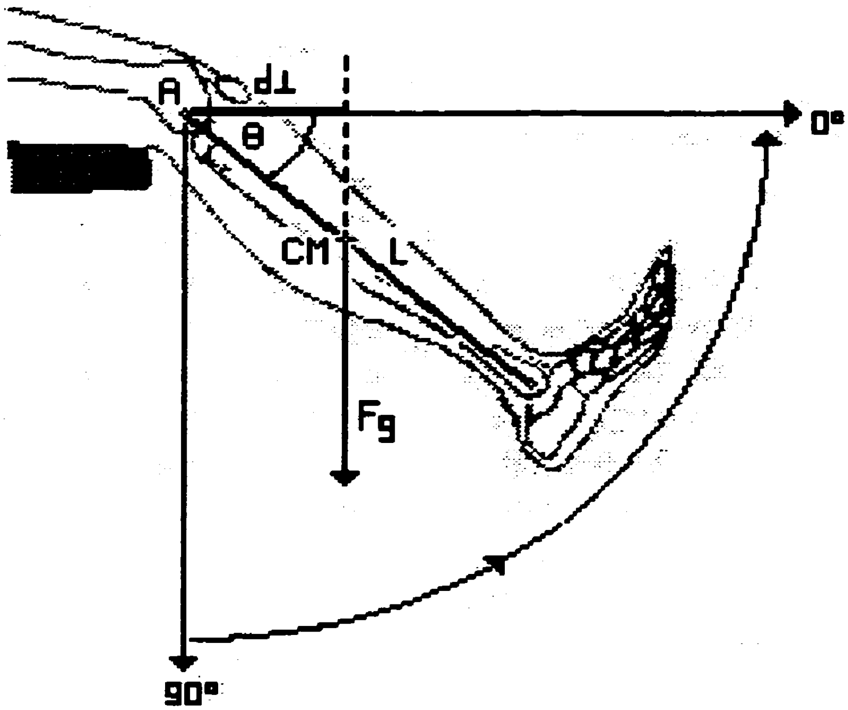


Figure 3-5: Illustration of the moment due to the weight of the leg (adapted from Baltzopoulos & Brodie, 1989).

Sample Calculation: The effect of the moment of the weight of the lower leg of a 65.9 kg person with a leg length of 0.445m at an angle of 30 degrees below the horizontal can be calculated as:

$$M_W = (0.06 \times BWt) \times (0.437 \times l \cos\theta)$$
$$= (0.06 \times (65.9kg \times 9.81m/s/s)) \times (0.437 \times 0.445 \times \cos30)$$
$$= \mathbf{6.73\ Nm}$$

The moment of the weight of the leg was then subtracted from the moment obtained by the Kin/Com (M_D) in order to give the resultant joint moment about the knee (RJM_K).

$$\mathbf{RJM_K = M_D - M_W}$$

RJM_K for the same sample calculation can be calculated as:

$$RJM_K = 16.6 \text{ Nm} - 6.73 \text{ Nm}$$
$$= \mathbf{9.87\ Nm}$$

Therefore, the resultant joint moment about the knee due to passive muscle resistance is 9.87 Nm.

The correction for the moment of the weight of the leg was applied throughout the entire range of motion. The zero value of the M_W was applied at the point when the leg was at an angle of approximately 90 degrees below the horizontal, which corresponded to a knee joint angle of approximately 110 degrees of flexion. This position was determined by the transition from negative torque values to positive torque values, as reported by the dynamometer. This transition occurred at about the same actuator arm position for all trials during pilot testing. This position was standardized, so that the same actuator arm position was used for the application of the moment of the weight of the correction for all test trials.

Once the RJM_K values were calculated for each leg of each subject, values for passive peak torque, joint angle at peak torque, maximal stiffness, and stiffness in a common range were determined. Passive peak torque was determined by the torque value at the end point of passive knee extension. The knee joint angle at the end point was also recorded. Maximal stiffness was determined by calculating the change in passive torque during the final 10 degrees of the knee extension range of motion. The values for maximal stiffness, in Nm/deg, were converted to Nm/rad to allow comparison to stiffness values reported in the literature.

Sample Calculation of Maximal Stiffness for Subject 1, Test 1 from Pilot Study:

Stiffness $= (T_f - T_i)/10\text{deg} \times 57.3$ deg/rad
$= (33.146 \text{ Nm} - 22.838 \text{ Nm})/10 \text{ deg} \times 57.3$ deg/rad
$= 1.031$ Nm/deg x 57.3 deg/rad
= 59.1 Nm/rad

Therefore, the maximal stiffness for Subject 1 in Test 1 was 59.1 Nm/rad.

The values for stiffness between 30 and 40 degrees from full extension, a range common to all subjects, were calculated in the same manner as the maximal stiffness values and were reported in Nm/rad.

Statistical Analysis

Several statistical analyses were performed to evaluate the relationship between the three clinical flexibility tests and the passive Kin/Com Dynamometer test, and to compare hamstring strain injured subjects to subjects with no history of hamstring injury. For all analyses, mean values were calculated to one decimal place for each test variable. All statistical analyses were performed using the Statview 4.0 statistical package on an IBM computer. Statistical significance levels were set at $p<0.05$.

Clinical Tests vs. Kin/Com Test Variables

The primary purpose of the study was to compare the measurement of hamstring flexibility by the Sit and Reach Test, the Active Knee Extension Test, and the Passive Knee Extension Test to the resistance to stretch during passive extension of the knee, as measured by the Kin/Com Isokinetic Dynamometer.

Single regression analyses were used to compare each of the clinical tests (independent variables) to each of the variables of the Kin/Com test (dependent variables). Regression equations were calculated for each significant result.

Independent Variables

1. Sit and Reach Test score
2. Active Knee Extension Test score
3. Passive Knee Extension Test score

Dependent Variables (Kin/Com)

1. Passive peak torque
2. Angle at passive peak torque
3. Maximal stiffness

4. Common stiffness

Injured Subjects vs. Non-injured Subjects Comparison

The second purpose of this study was to examine the differences in flexibility measurement scores between subjects with a previous hamstring injury and subjects with no history of hamstring injury. For this analysis, the subjects in the Non-injured group (N=10) were matched with Injured group subjects (N=10) according to sport, position, weight, height and limb dominance. The Non-injured group limbs were then separated into 'injured' and 'uninjured' groups according to the injured and uninjured limbs of their Injured group counterparts. Seven, two-way analyses of variance (ANOVA) with one between subjects factor (group membership) and one within subjects factor (limb) were performed for each dependent variable listed below. A Tukey's Post Hoc Test was performed on any significant result to determine where the significant differences existed.

Dependent Variables

1. Sit and Reach Test score
2. Active Knee Extension Test score
3. Passive Knee Extension Test score
4. Peak Torque (Kin/Com)
5. Angle at Peak Torque (Kin/Com)
6. Stiffness in final 10 degrees
7. Stiffness in common 10 degree range

Pilot Study

A pilot study was performed with the goals of (1) examining the possibility of measuring the resistance to passive stretch using the Kin/Com dynamometer (Model # 500-9), (2) to give the investigator the opportunity to gain some practical experience in collecting data using the flexibility test protocols, (3) to ensure that instructions to the subjects are clear and concise, and make modifications where needed, and (4) to collect and analyze preliminary data. The investigator received ethics approval from the Education/Nursing Research Ethics Review Board prior to pilot testing.

Subjects

Three active and healthy male subjects participated in the pilot study. The subjects were recruited by personal communication with the investigator. All of the subjects were free of lower limb pathology and pain at the time of the pilot study. Their respective anthropometric data is given in the following table.

Table 3-1: Subject Characteristics

Subject	Age, yrs	Height, m	Weight, kg	Thigh Length, m	Shank Length, m
Subject # 1	28	1.75	78.5	0.395	0.445
Subject # 2	24	1.67	77.5	0.413	0.424
Subject # 3	28	1.75	78.8	0.4	0.436

Materials

The materials used in the pilot study were the same as those listed previously in this chapter.

Protocol

The protocol for the pilot study was similar to the protocol previously described in this chapter. Upon arrival at the Biomechanics Lab in the Max Bell Centre, subjects read and signed the Informed Consent, which was then signed and dated by the Investigator and a witness. Anthropometric measurements (ht, wt, leg length, thigh length) were taken for each subject and each subject performed a warm-up prior to testing, which consisted of 5 static hamstring stretches (toe-touches), each lasting 30 seconds. Each subject performed the Sit and Reach, Active Knee Extension, Passive Knee Extension, and Dynamometer tests, as previously described, with the same end point determination for the active and passive knee extension tests, and the passive dynamometer test.

Due to the backward slope of the Kin/Com backrest, the passive dynamometer test utilized a modified thigh pad, which raised the thigh approximately 15 degrees above horizontal in order to maintain the hip at approximately 90 degrees of flexion. The same modified thigh pad was used for all subjects. The same starting position was used for all test trials.

The subjects were tested on their right leg only (arbitrary selection) and each subject repeated the protocol with the same limb on subsequent days in a test-retest format.

Data Analysis

The methods of data analysis were the same as those previously described in this chapter. The best score out of three trials was used as the final score for the SR test. The AKE and PKE tests were videotaped, with the resulting video used for determining the knee joint angle during subsequent analysis. The final scores for the AKE and PKE tests were taken from the average of the three respective angular position values.

A problem was discovered during analysis of the passive torque and actuator arm angular position values, as reported by the Kin/Com software. The variables from Kin/Com (force, arm angle) are sampled at 100 Hz, meaning that the force value and the arm angle are determined every 1/100th of a second. The Kin/Com software automatically calculates the torque for each sample, using the actuator arm radius, and both the force and torque values are reported. The limitation of the Kin/Com software is that the angle of the actuator arm is reported to the nearest degree, even though the actuator arm is moving through that degree. There is no distinction in position between samples taken at 77.1 degrees and 77.8 degrees, for example, which are both reported as 77 degrees. This limitation is more apparent at slower angular velocities, such as the 5 deg/sec used in this study. At this angular velocity, there are approximately 20 separate values for force and torque, corresponding to 20 separate samples, reported for the same angle.

In an attempt to solve this problem, a single sample from each angle was used to represent that angle. The 5th sample was recorded, as well as every subsequent 20th sample throughout the entire range. By starting on the 5th sample, the value reported for each angle would then be taken from about the middle of the values reported for that angle. The same method was used for all trials and all subjects. The average of the torque values for each angle from the three trials was taken as the final torque value for that angle.

The moment due to the weight of the leg for each subject was calculated from the anthropometric measurements made prior to testing, as outlined by Kellis & Baltzopoulos (1996). The correction for the moment due to the weight of the leg was applied through the entire range of motion. The zero value for the M_W was applied when the leg was at an angle of approximately 90 degrees relative to the horizontal. This position was determined by the transition from negative torque values to positive torque values, as reported by the dynamometer. This transition occurred at about the same actuator arm position for all trials. This position was standardized, so that the same actuator arm position was used for the application of the moment of the weight correction for all test trials. An example of the Microsoft Excel™ file used for calculations is given in Appendix B.

Peak passive torque was determined by the torque value at the end point of passive knee extension. The knee joint angle at the end point was also recorded. Maximal stiffness was determined by calculating the change in passive torque during the final 10 degrees of the knee extension range of motion. The stiffness in a common 10-degree range was also calculated, corresponding to the same range as the maximal stiffness of the subject with the smallest range of motion. These values, in Nm/deg, were then converted to Nm/rad for comparison to stiffness values as reported in the literature.

Sample Calculation of Maximal Stiffness for Subject 1, Test 1:

$$
\begin{aligned}
\text{Stiffness} &= (T_f - T_i)/10\text{deg} \times 57.3 \text{ deg/rad} \\
&= (33.146 \text{ Nm} - 22.838 \text{ Nm})/10 \text{ deg} \times 57.3 \text{ deg/rad} \\
&= 1.031 \text{ Nm/deg} \times 57.3 \text{ deg/rad} \\
&= \mathbf{59.1\ Nm/rad}
\end{aligned}
$$

Therefore the maximal stiffness for Subject 1 in Test 1 is 59.1 Nm/rad.

Results

The results of the pilot study are summarized in Table 3-2. The final scores for the SR, AKE, and PKE tests, calculated from respective test trials (Appendix C), are given for each subject and each day, as well as the average peak torque values and knee joint angle at peak torque (end range) from the passive dynamometer tests. The AKE, PKE, and dynamometer angular position values represent the knee flexion angle in degrees from full extension. The values for maximal stiffness (MS) and common stiffness (CS), or stiffness in a common range, are given in Nm/rad.

Table 3-2: Results of Pilot Study

Test	**Sub 1** Test 1	**Sub 1** Test 2	**Sub 2** Test 1	**Sub 2** Test 2	**Sub 3** Test 1	**Sub 3** Test 2
SR, cm	32	34	35	35	43	45
AKE, deg	24.7	17.4	16.7	13.7	8.7	8.7
PKE, deg	20.7	22	10.7	7	12	9
PT, Nm	33.1	30.5	31.6	31.0	29.6	29.8
Angle at PT, deg	24	27	10	8	6	8
MS, Nm/rad	59.1	55.2	53.3	52.1	48.2	41.8
CS, Nm/rad	59.1	55.2	30.6	28.0	22.2	21.7

Graphs expressing the passive torque curves from the Kin/Com test for each subject and test are displayed in Figures 3-4 to 3-9.

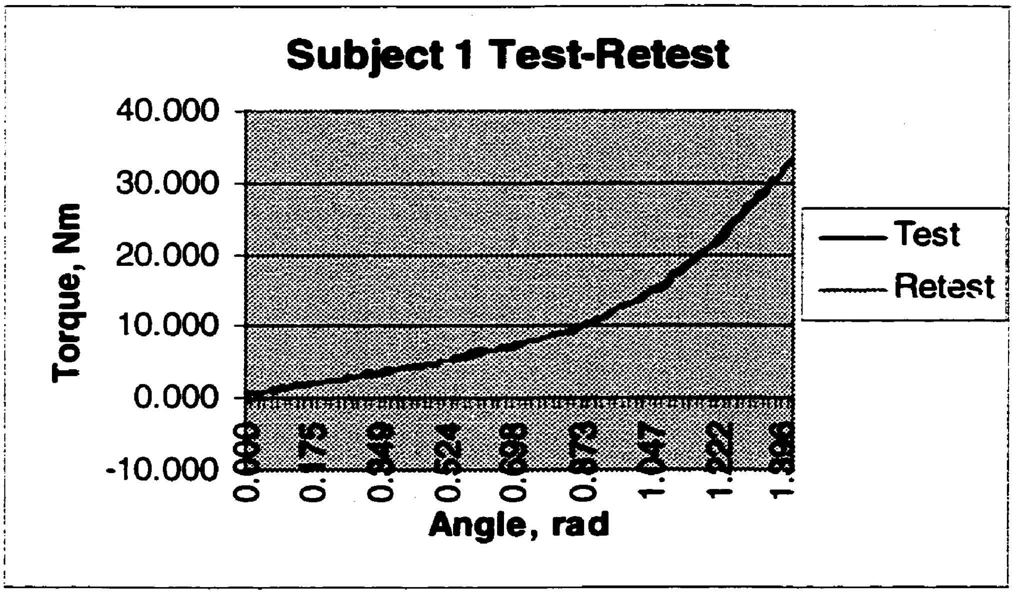


Figure 3-6: Test-Retest passive torque curves for Subject 1

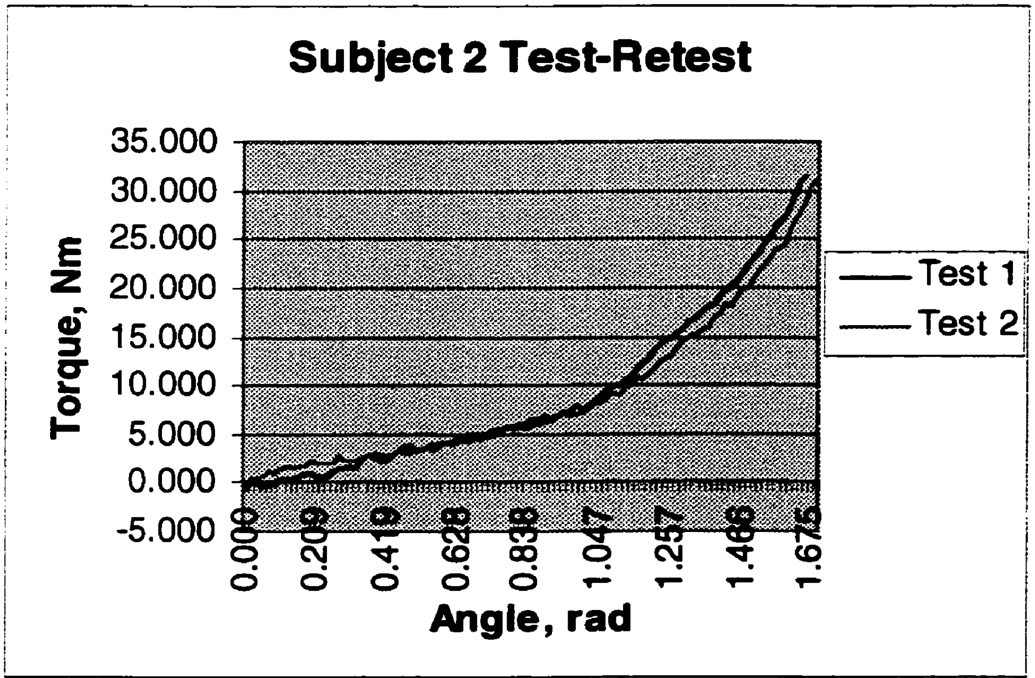


Figure 3-7: Test-Retest passive torque curves for Subject 2

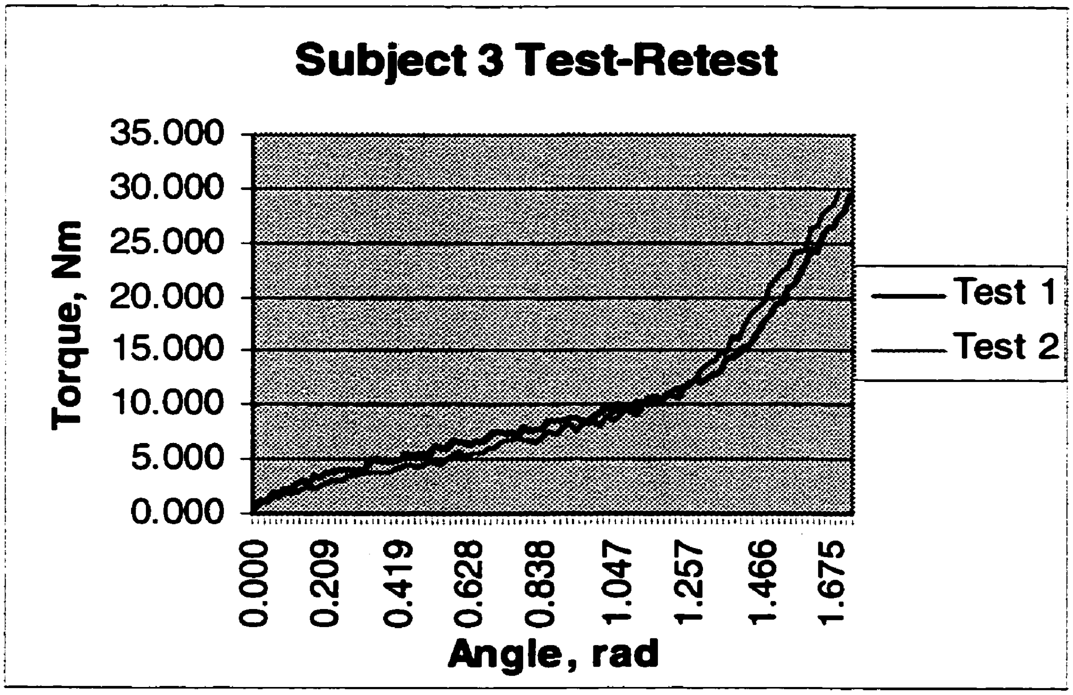


Figure 3-8: Test-Retest passive torque curves for Subject 3

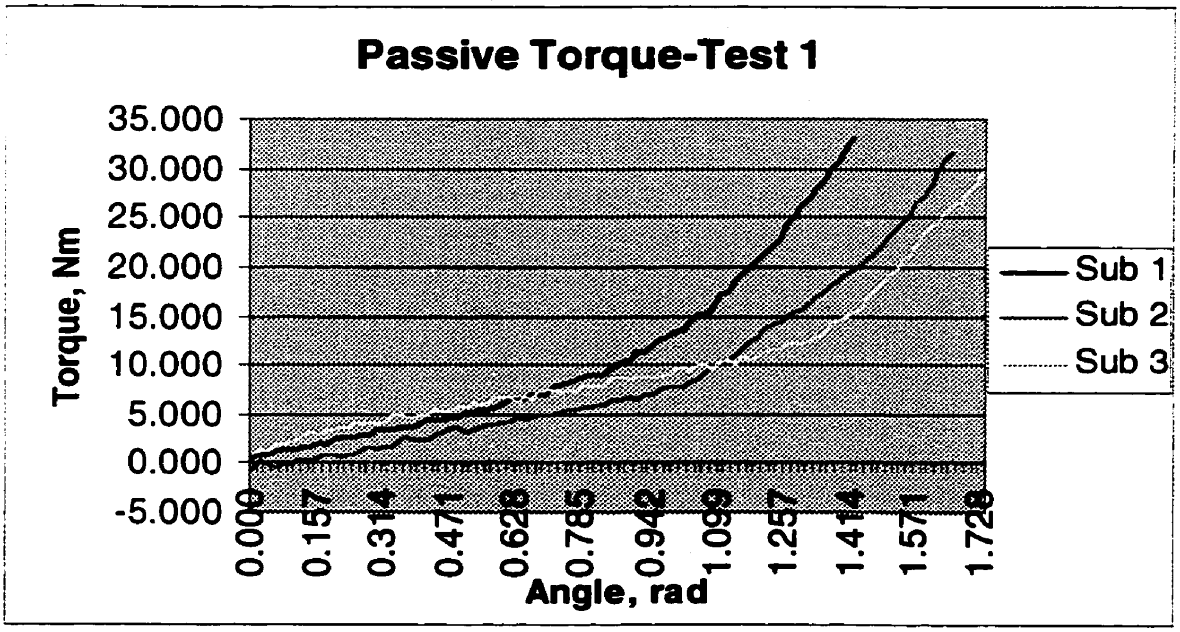


Figure 3-9: Comparison of passive torque curves for all subjects in Test 1

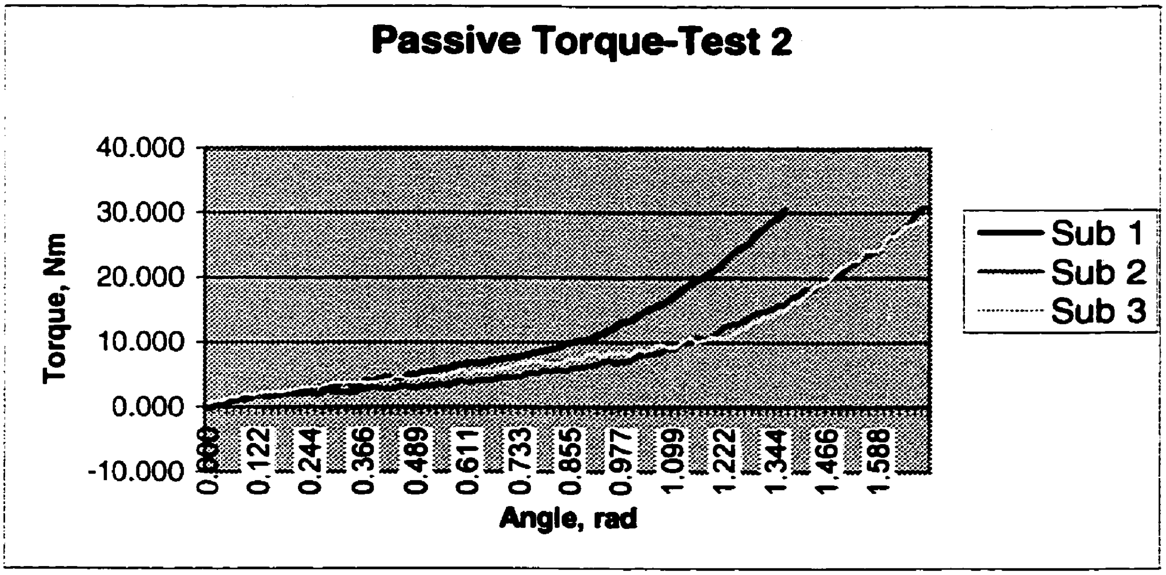


Figure 3-10: Comparison of passive torque curves for all subjects in Test 2

Discussion

Because of the small sample size of the study, a statistical analysis could not be carried out, and no conclusions can be made based on the results of the pilot study. However, some interesting trends in the data can be noted. Subjects who performed better on the SR test also performed better on the AKE and PKE tests. The angular position values for the AKE test were higher than the PKE test values for Subjects 1 and 2, but not for Subject 3. The values for peak torque were similar for all three subjects and for both tests, with values between 29.6 Nm and 33.1 Nm, although the joint angles at which the values occurred were different. The peak torque values were similar to the mean peak torque value of 31.6 ± 4.1 Nm reported by Magnusson et al (1997), but were between 10-15 Nm lower than those reported by other studies (Magnusson et al, 1995a; Magnusson et al, 1996a; Magnusson et al, 1996b).

The values for maximal stiffness were similar for all three subjects, but the values were lower in the subjects with a greater range of motion. The maximal stiffness values, 41.8 Nm/rad to 59.1 Nm/rad, were similar to the range of values, 28 ± 2.9 Nm/rad to 54.9 ± 6.5 Nm/rad, reported in the literature (Magnusson et al, 1995a; Magnusson et al, 1996a; Magnusson et al, 1996b; Magnusson et al; 1997). Common stiffness values were lower in those subjects with a greater range of motion.

The average passive torque curves of Test 1 and Test 2 were similar for each subject. This suggests that the passive resistance to knee extension can be measured by the Kin/Com isokinetic dynamometer (Model #500-9) using the described protocol.

CHAPTER 4

Results

Subjects for this study included 20 elite male athletes from the University of Manitoba, with 10 subjects in the Experimental (injured) group (age = 22.4 yrs, ht = 1.829 m, wt = 87.89 kg) and 10 subjects in the Control (non-injured) group (age = 21.6 yrs, ht = 1.822 m, wt = 84.84 kg). These athletes were members of the varsity football (N=15) and track (N=5) teams.

Table 4-1. Descriptive Subject Data, mean (SD)

Group	Age	Height, m	Weight, kg	Years Competing
Injured	22.4 (2.22)	1.83 (0.03)	87.9 (10.98)	3 (0.94)
Noninjured	21.6 (2.95)	1.82 (0.06)	84.8 (9.36)	3 (1.76)

Flexibility Test and Dynamometer Comparison

Regression coefficients for the correlation between the three clinical tests (Sit and Reach, Active Knee Extension, Passive Knee Extension) and the variables from the Kin/Com Isokinetic Dynamometer test (peak torque, angle at peak torque, maximal stiffness, common stiffness) are reported in Table 4-2. For the Sit and Reach Test, there was a significant relationship with the angle at peak torque ($p < 0.01$), maximal stiffness ($p < 0.05$), and common stiffness ($p < 0.01$). A scattergram illustrating the relationship between the Sit and Reach score and the angle at peak torque is reported in Figure 4-1. A higher Sit and Reach Test score was related to a lower angle at peak torque. A scattergram illustrating the relationship between the Sit and Reach score and the maximal stiffness is reported in Figure 4-2. A higher Sit and Reach score was related to a higher maximal stiffness. A higher Sit and Reach score was also correlated to a lower common stiffness. The Active Knee Extension Test was significantly correlated to the angle at peak torque ($p < 0.01$), as illustrated by a scattergram reported in Figure 4-3, and common stiffness ($p < 0.01$). A lower Active Knee Extension Test score was related to a lower angle at peak torque and a lower common stiffness. Significant correlation was also noted between the Passive Knee Extension Test and the angle at peak torque ($p < 0.01$), as illustrated by a scattergram reported in Figure 4-4, as well as common stiffness ($p < 0.01$). A lower score on the Passive Knee Extension Test was related to a lower angle at peak torque and a lower common stiffness. There were no other significant relationships noted between the clinical tests and Kin/Com test variables.

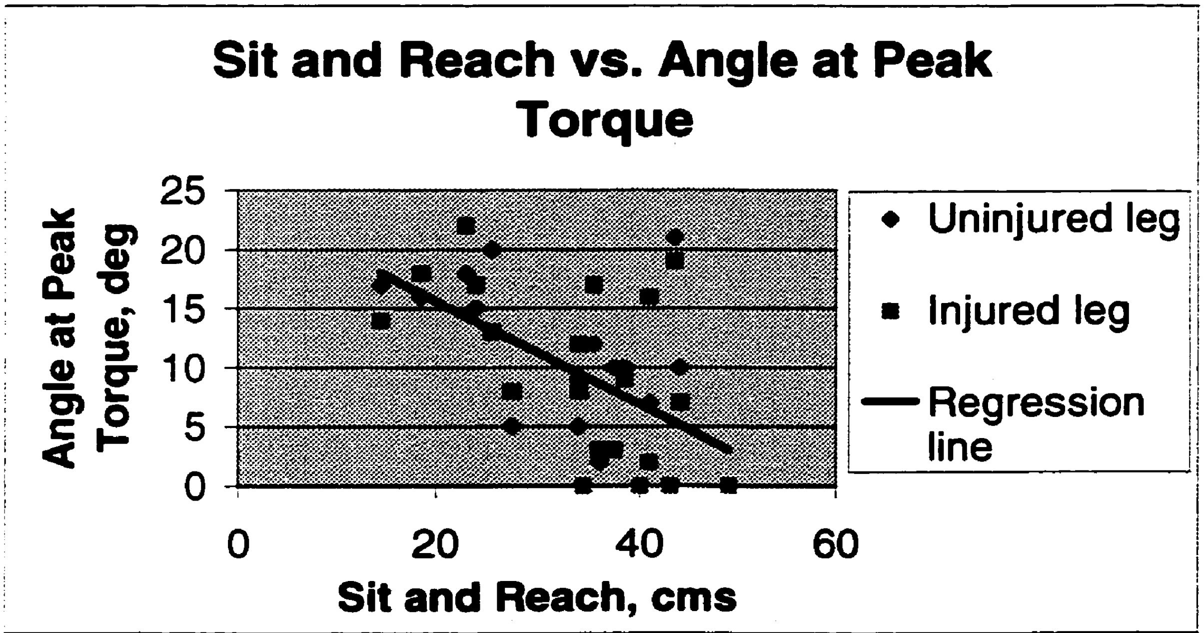


Figure 4-1. Sit and Reach vs. Angle at Peak Torque Regression, r = -0.407

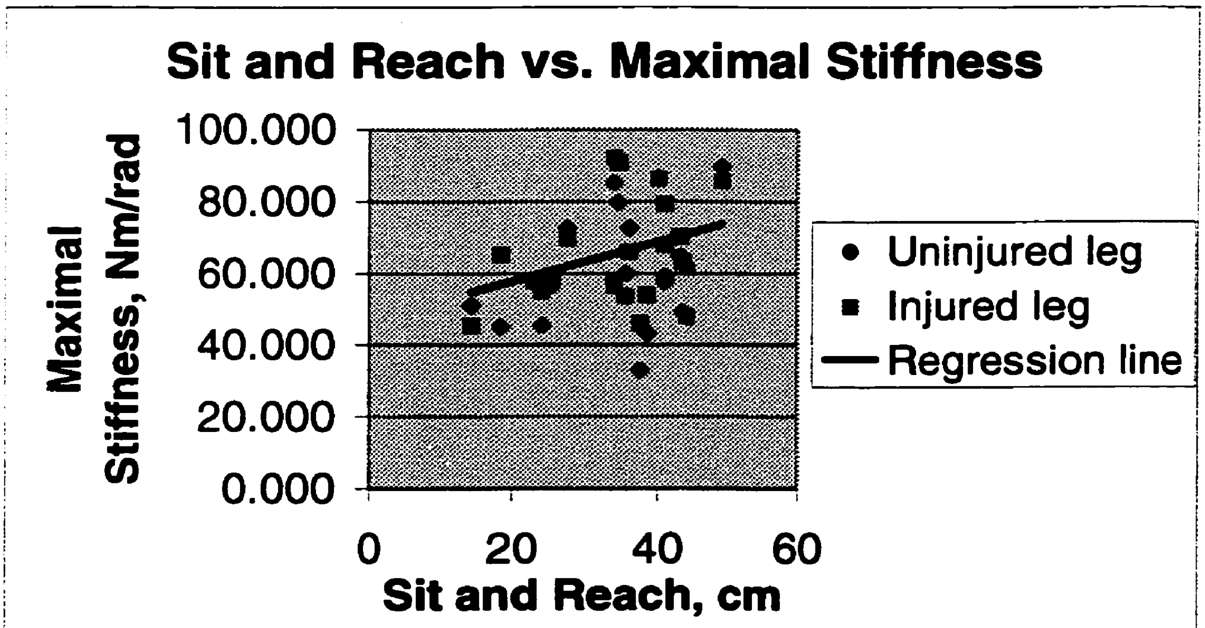


Figure 4-2. Sit and Reach vs. Maximal Stiffness Regression, r = 0.553

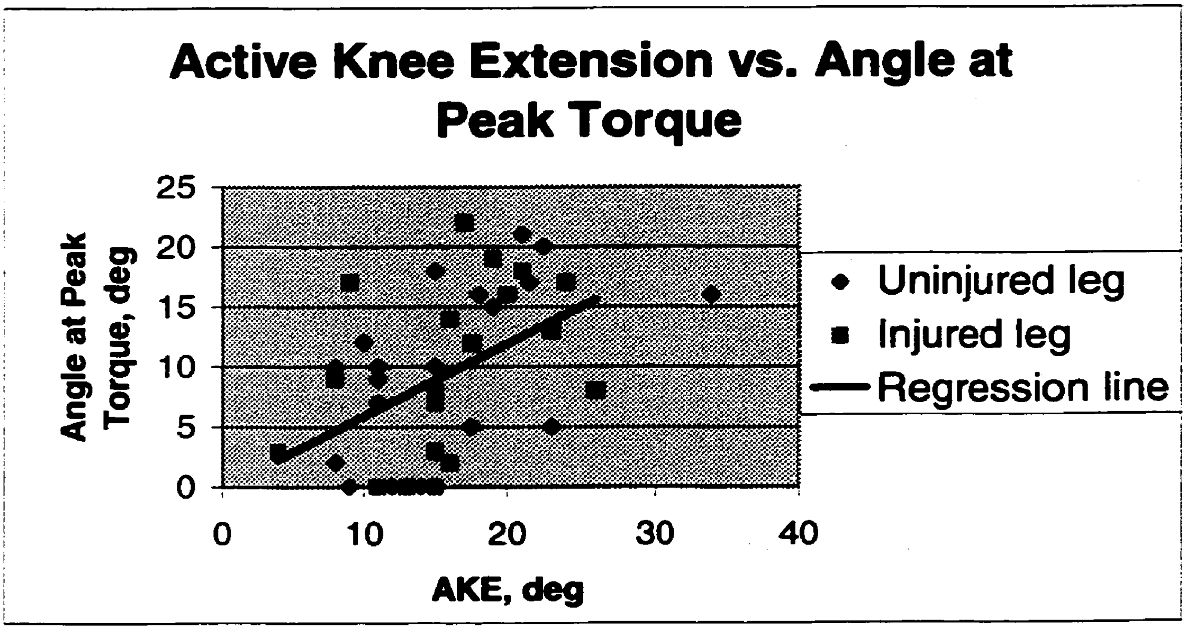


Figure 4-3. Active Knee Extension vs. Angle at Peak Torque Regression, r = 0.604

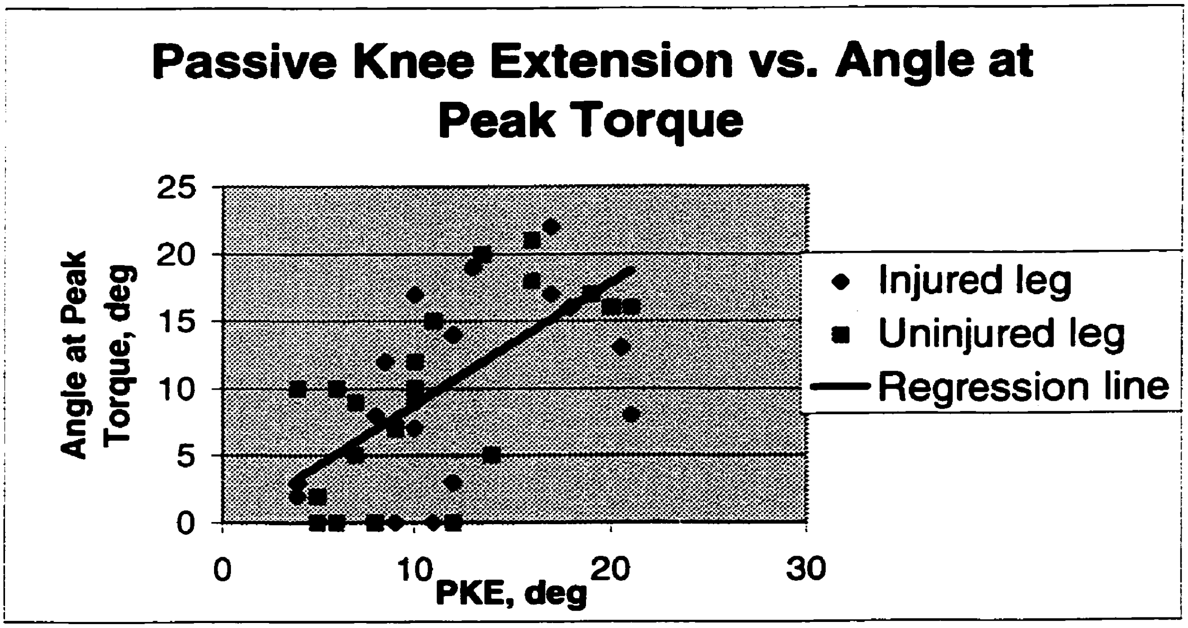


Figure 4-4. Passive Knee Extension vs. Angle at Peak Torque Regression, r = 0.892

Table 4-2. Summary of Regression Coefficients between the Sit and Reach, Active Knee Extension, and Passive Knee Extension Tests and the Kin/Com test variables (N=20).

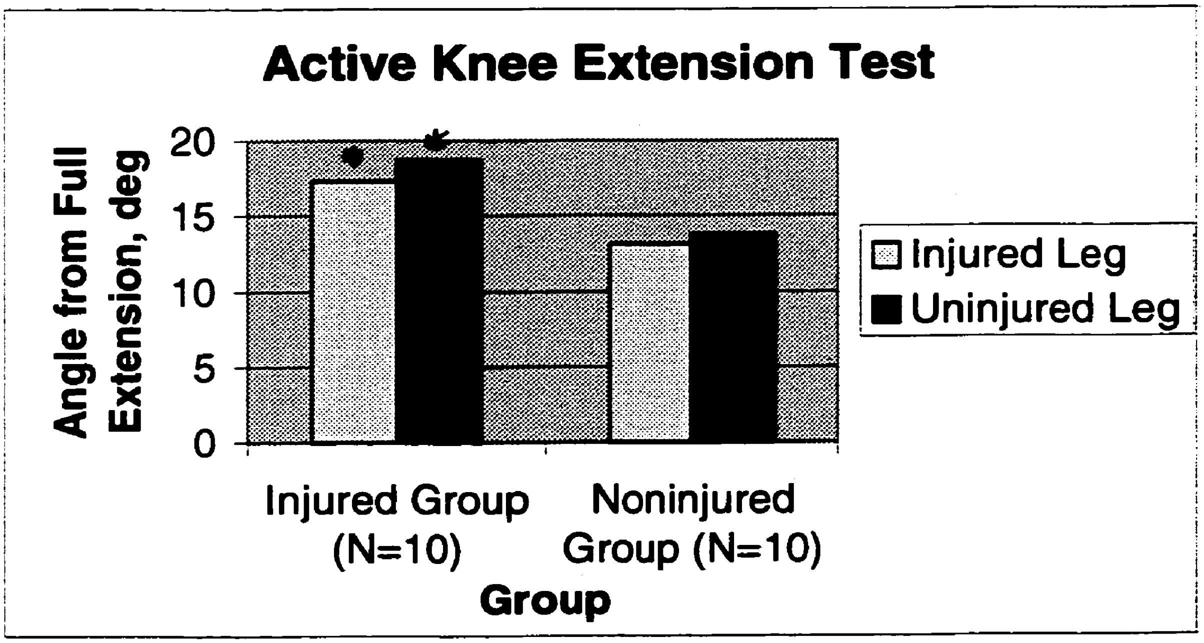
Clinical Test	Kin/Com Variable	Regression Coefficient	p value
Sit and Reach	Peak Torque	0.111	0.46
	Angle at PT	-0.407	0.001 **
	Maximal Stiffness	0.553	0.03 *
	Common Stiffness	-0.568	0.002 **
Active Knee Extension	Peak Torque	-0.129	0.57
	Angle at Peak Torque	0.604	0.001 **
	Maximal Stiffness	-0.190	0.64
	Common Stiffness	0.784	0.006 **
Passive Knee Extension	Peak Torque	-0.241	0.37
	Angle at Peak Torque	0.892	0.0001 **
	Maximal Stiffness	-0.771	0.13
	Common Stiffness	0.596	0.006 **

* $p < 0.05$, ** $p < 0.01$

Injured and Non-injured Group Comparison

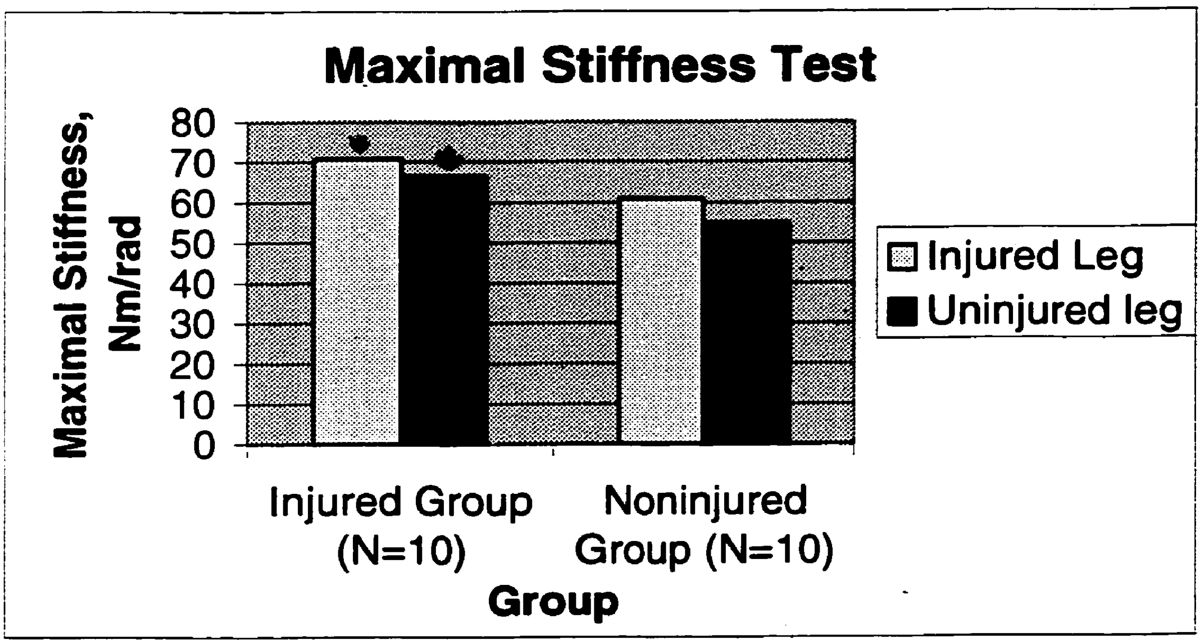
The means and standard deviations for the Sit and Reach, Active Knee Extension, and Passive Knee Extension tests as well as for the peak torque, angle at peak torque, maximal stiffness, and common stiffness variables for the Kin/Com Isokinetic Dynamometer test are reported in Table 4-3. These values are reported for the Injured and Non-Injured groups and the injured and un-injured limbs.

A two-way analysis of variance was used to detect differences between Injured and Non-injured subjects and between injured and uninjured limbs. The analysis of variance revealed a significant difference ($p < 0.05$) in Active Knee Extension Test scores between the Injured and Non-injured groups. A subsequent Tukey's test revealed that the Injured group had significantly less range of motion than the Non-injured group in both the injured legs and uninjured limbs during active knee extension (Figure 4-5). There was also a significant difference ($p < 0.05$) in maximal stiffness values between the Injured and Non-injured groups. Subsequently, a Tukey's test showed that the maximal stiffness values for the Injured group were significantly higher than values for the Non-injured group for both the injured and uninjured legs (Figure 4-6). There were no other significant differences between the groups for any of the other test variables.



* significantly different from Non-injured group comparison leg, $p < 0.05$

Figure 4-5. Active Knee Extension Test: Injured (N=10) vs. Non-injured (N=10) groups.



* significantly different from Non-injured group comparison leg, $p < 0.05$

Figure 4-6. Maximal Stiffness: Injured (N=10) vs. Non-injured (N=10) groups

Hamstring Injury Questionnaire

Descriptive data relating to the sport, position, lower limb dominance, injured extremity and duration of injury for the Experimental and Control Groups may be found in Table 4-3. In addition, the hamstring injury questionnaire revealed the following information:

- All subjects were involved in a lower body strength-training program.
- 50 percent (5/10) of the injured subjects were involved in a flexibility program.
- 20 percent (2/10) of the non-injured subjects were involved in a flexibility program.
- 40 percent (4/10) of the injured subjects reported their hamstring injuries as recurrent.
- 80 percent (8/10) of the injured athletes injured their dominant limbs
- The average time away from activity due to injury was 15.7 days
- 20 percent (4/20) of the athletes participated in both sports.

Table 4-3. Summary of one-way ANOVA for the Sit and Reach test and two-way ANOVA for the clinical tests and the Kin/Com Dynamometer variables.

Variable	Group	Injured Limb mean ± SD	Uninjured Limb mean ± SD	F value	p value
Sit and Reach (cms)	INJ	35.4 ± 9.5	Same	0.285	0.60
	NON	33.1 ± 9.4	Same		
Active Knee Extension (deg)	INJ	17.3 ± 5.2	18.7 ± 7.7	Group: 6.154	0.02 *
				Leg: 0.328	0.57
	NON	13.1 ± 5.4	13.8 ± 4.4	G x L: 0.028	0.87
Passive Knee Extension (deg)	INJ	12.5 ± 5.7	12.3 ± 6.0	Group: 1.557	0.22
				Leg: 0.059	0.81
	NON	9.8 ± 4.4	10.9 ± 4.5	G x L: 0.165	0.69
Peak Torque (Nm)	INJ	46.4 ± 10.4	43.2 ± 8.7	Group: 3.215	0.08
				Leg: 1.215	0.28
	NON	41.4 ± 5.5	38.8 ± 7.5	G x L: 0.017	0.90
Angle at Peak Torque (deg)	INJ	8.9 ± 7.1	10.3 ± 8.2	Group: 0.001	0.99
				Leg: 0.716	0.40
	NON	8.4 ± 8.0	10.9 ± 5.5	G x L: 0.056	0.81
Maximal Stiffness (Nm/rad)	INJ	70.8 ± 13.8	66.5 ± 15.9	Group: 5.667	0.02 *
				Leg: 1.305	0.26
	NON	60.8 ± 13.1	54.8 ± 14.9	G x L: 0.034	0.85
Common Stiffness (Nm/rad)	INJ	43.1 ± 10.9	45.0 ± 9.8	Group: 1.825	0.19
				Leg: 0.694	0.41
	NON	43.2 ± 12.1	35.7 ± 9.5	G x L: 1.903	0.18

Group: between Injured (Experimental) and Non-injured (Control) groups, Leg: between injured and un-injured limbs, GxL: group and leg interaction.

Table 4-4. Summary of Activity and Hamstring Injury Questionnaire.

Group	Subject	Sport	Position*	Years Competing	Strength Program	Flexibility Program	Dominant Limb	Injured Limb	Duration of Injury (days)**
EXP (Injured)	1	Track	SPR/JPR	3	Yes	Yes	Right	Right	5
	2	Football	RB	2	Yes	No	Right	Right	1
	3	Football	WR	2	Yes	No	Right	Right	10
	4	FB/Track	DB/SPR	4	Yes	No	Left	Left	1
	5	Football	LB	4	Yes	No	Right	Right/Left	10
	6	FB/Track	LB/SPR	4	Yes	Yes	Right	Right	21
	7	Football	WR	2	Yes	No	Left	Left	36
	8	Track	SPR/JPR	2	Yes	Yes	Left	Left	40
	9	FB/Track	DB/SPR	4	Yes	Yes	Right	Left	12
	10	Track	SPR	3	Yes	Yes	Right	Left	21
		FB-Football							Mean = 15.7 SD = 13.7
CON (Non-injured)	1	Track	SPR	4	Yes	Yes	Right		
	2	Track	SPR	3	Yes	No	Right		
	3	Football	RB	4	Yes	No	Left		
	4	Football	LB	2	Yes	No	Right		
	5	Football	DB	2	Yes	No	Right		
	6	FB/Track	RB/SPR	7	Yes	Yes	Right		
	7	Football	WR	3	Yes	No	Left		
	8	Football	WR	1	Yes	No	Right		
	9	Football	WR	1	Yes	No	Right		
	10	Football	RB	3	Yes	No	Right		
		FB-Football							

* SPR – Sprinter, JPR – Jumper, RB – Running Back, WR – Wide Receiver, LB – Line Backer, DB – Defensive Back

** refers to time away from full activity

Chapter 5

Discussion

Hamstring strain injury is a common injury among athletes involved in sprinting activities. Recovery from a hamstring strain injury is primarily determined by full recovery of strength and pain-free range of motion about the hip and knee joints (Andrews, Harrelson, & Wilk, 1998). Once these have been achieved, the athlete follows a gradual return to full activity. The athlete increases range of motion, or flexibility, by progressive stretching regimes, which will increase the stretch tolerance of the athlete (Magnusson et al, 1996c). Therapists facilitate flexibility increases through the use of various modalities (massage, ultrasound) to make the tissue more pliable. The aim is to reduce the amount of fibrosis within the tissue and remodel the scar tissue into healthy elastic tissue. Scar tissue within the muscle can increase the stiffness of the muscle due to its inelastic properties (Nikolaous et al, 1987). Methods for accurate determination of the stiffness of skeletal muscle exist through the use of an Isokinetic dynamometer (Magnusson, 1998), but the prevalence of this technique in a clinical setting in relation to injury rehabilitation has not been documented. Clinically, therapists rely on their sense of touch to determine day-to-day changes in the tightness and stiffness in the tissue during stretching or massage. However, this method is subjective in nature. The use of hand held dynamometers to measure the resistive force during assisted stretching is becoming more prevalent, but this technique is limited by potential errors during application and the lack of studies in the literature for force value comparisons (Fredriksen et al, 1997).

The primary objective of this study was to examine the relationships between the Sit and Reach, Active Knee Extension, and Passive Knee Extension Tests and the resistance offered by the knee flexors during passive extension of the knee, as measured by the Kin/Com Isokinetic Dynamometer. The dependent variables examined were peak torque, angle at peak torque, maximal stiffness, and common stiffness.

A secondary objective of the study was to determine whether there were significant differences in the three Clinical Test scores and the Kin/Com Test variables between subjects that had sustained a hamstring strain injury and subjects with no history of hamstring strain injury.

This study will enable the therapist to more accurately determine the amount of healing in a strained hamstring by providing additional information regarding the function and stiffness properties of the recovering muscle.

Subjects

Participants in this study included male members of the varsity track (N=5) and varsity football (N=15) teams at the University of Manitoba. Members of the varsity track team were all sprinters, with two participating in jumping events (long jump and/or triple jump) as well. Members of the varsity football team who were recruited consisted of running backs, linebackers, defensive backs, and wide receivers. These positions were selected because a sprinting movement is a major component of each position, and these were among the same positions used by Worrell et al (1991) to compare passive knee extension flexibility between hamstring injured and non-injured athletes. Four of the football players participated in track practice during the football off-season in order to improve their speed and acceleration.

All subjects in the Injured group sustained their injuries during a maximal sprinting movement either in competition or during a training session. The majority of the injured subjects (70%) sustained a hamstring strain injury in their dominant limb, which differs from the findings of Worrell et al (1991). Among 16 Injured group subjects, Worrell et al (1991) found that only 6 (37%) subjects injured their dominant lower extremity.

Analysis of Test Results

Sit and Reach Test

Mean Sit and Reach (SR) scores were 35.4 ± 9.5 cm and 33.1 ± 9.4 cm for the Injured and Non-injured groups respectively. A score of 25 cm indicates the ability to reach the soles of the feet, with scores greater than 25 cm referring to the ability to reach past the toes. The SR scores in the present study were greater than values reported in the literature. Jackson and Langford (1989) reported a mean SR score of 29.41 ± 11.43 cm among 52 male volunteers with no history of injury. A study by Hreljac et al (2000) compared the SR scores between male and female long distance runners with or without previous overuse injuries at or below the knee. Mean scores for the injured and injury-free groups were –3.7 ± 11.3 cm and 3.2 ± 10.2 cm respectively. The scores referred to the distance from (negative values) and past (positive values) the soles of the feet, with a zero score indicating the ability to reach the soles of the feet. These measurements would correspond to values of 21.3 ± 11.3 cm for the injured group and 28.2 ± 10.2 cm for the injury-free group. The authors speculated that the lack of flexibility in the injured group subjects may have increased the stiffness of the muscles and helped to cause the injuries.

A study by Chang et al (1988) compared the SR flexibility of 10 male power lifters to 10 male, non-athletes (controls). Mean SR scores were reported as 7.6 ± 4.0 cm past the feet for the power lifters and 0.8 ± 5.9 cm from the feet for the controls, with the soles of the feet used as the zero point. These values would correspond to scores of 32.6 ± 4.0 cm and 24.2 ± 5.9 cm for the lifters and controls, respectively, using 25 cm as the soles of the feet.

In comparison to age-group peers, the subjects in the present study were considered to have “Good” to “Excellent” SR flexibility (Thorndyke, 1995; ACSM, 2000). Orchard et al (1997) studied flexibility differences between hamstring-strain injured and non-injured professional footballers using the SR test, but mean values were not reported in the study because no significant difference between the two groups was found.

Active Knee Extension Test

The Active Knee Extension Test (AKE) is a hamstring flexibility test that may be used by a therapist to determine the progress of increasing the range of motion about the knee following hamstring strain injury. The AKE test is an easy test to administer and has a high reliability (ICC = 0.98-0.99) provided the hip angle can be maintained at an angle of 90 degrees of flexion (Gajdosik & Lusin, 1983; Webright et al, 1997). It has been suggested that the AKE test may represent the initial or un-stretched length of the hamstrings (Gajdosik et al, 1993).

Mean AKE values for the Injured group were 17.3 ± 5.2 and 18.7 ± 7.7 degrees from full extension for the injured and uninjured limbs, respectively. For the Non-injured group, the AKE values for the matched injured and uninjured limbs were 13.1 ± 5.4 and 13.8 ± 4.4 degrees from full extension, respectively. These values were closer to full extension than the AKE values reported in the literature.

Gajdosik & Lusin (1983) reported mean AKE values of 32.8 ± 16.75 and 37.6 ± 16.73 degrees from full extension in a study of 15 healthy males. Bruce (1989) reported AKE values of 15.2 ± 8.77 and 15.4 ± 10.37 degrees from full extension for the right and left limbs of Non-injured male subjects, respectively, and 19.1 ± 8.52 and 15.1 ± 9.81 degrees from full extension for the right and left limbs of male subjects with previous hamstring strain injuries, respectively. Sullivan et al (1992) reported mean Active Knee Extension values of 29.8 ± 12.82, 26.7 ± 11.62, 34.1 ± 10.03, and 36.1 ± 10.56, measured in degrees from full extension, for 20 male and female volunteers split into four groups. However, comparison of the present study to these values may not be fair as one of the inclusion criteria for Sullivan et al's study was having hamstring flexibility of more than 20 degrees from full extension as measured by the AKE test (Sullivan et al, 1992). Cameron & Bohannon (1993) measured the hamstring flexibility of 23 healthy subjects using the AKE test. However, values were reported as the mean absolute difference between test and retest results, thus negating comparison to the AKE values of the present study. Gajdosik et al (1993) reported a mean AKE value of 43.0 ± 10.2 degrees from full extension in a study of 30 healthy males, although subjects included in the study were limited to those with limited flexibility (i.e. a straight leg raise score of less than 90 degrees). Hahn et al (1999) reported mean AKE values of 37 ± 12.5 and 34 ± 13.2 (degrees from full extension) for healthy male athletes aged 18-20 years (N= 49) and 21-24 years (N=52), respectively.

The AKE values for the present study were closer to full extension (0°) than those reported in the literature, suggesting that the subjects in the present study had greater range of motion and better flexibility. These differences may be due to the use of video analysis instead of a flexometer or a goniometer in the determination of knee joint angle, the use of a cradle for stabilization of the thigh, or differences in study populations.

Passive Knee Extension Test

The Passive Knee Extension (PKE) test is another flexibility test that may be used by therapists to measure the range of motion progress of a hamstring-injured athlete during rehabilitation. It can be performed almost anywhere the athlete can lie on his/her back. Measurements can be made with a goniometer, flexometer, or by the use of video analysis and is highly reliable (ICC = 0.90-0.98), providing the hip can be maintained at an angle of 90 degrees of flexion (Worrell et al, 1991; Bandy et al, 1998; Hartig & Henderson, 1999). It has been suggested that the PKE test represents a measure of the maximum or fully stretched length of the hamstrings (Gajdosik, 1991; Gajdosik et al, 1993).

Mean PKE values for the Injured group for the injured and uninjured limbs were 12.5 ± 5.7 and 12.3 ± 6.0 degrees from full extension, respectively. For the Non-injured group, mean PKE values were 9.8 ± 4.4 and 10.9 ± 4.5 degrees from full extension for the matched injured and uninjured limbs, respectively.

The values reported in the present study were lower than most values reported in the literature, relating to greater passive range of motion about the knee. A study by Worrell et al (1991) measured the bilateral PKE flexibility of hamstring injured and non-injured athletes. The authors reported mean PKE values, in degrees from full extension, of 37.4 ± 10.78 and 32.2 ± 13.14 for the respective injured and uninjured limbs of the Injured group subjects, and 22.6 ± 8.00 and 22.3 ± 8.23 for the matched injured and uninjured limbs of the Non-injured group (Worrell et al, 1991). Gajdosik et al (1993) reported a mean PKE value of 31.0 ± 7.5 degrees from full extension in a study of 30 healthy male subjects with limited flexibility (a straight leg raise test score of less than 90 degrees). Krivickas and Feinberg (1996) reported a mean PKE value of 26 ± 13 degrees from full extension in a study of the flexibility of 131 healthy male college athletes. A study by Hartig & Henderson (1999) measured the PKE flexibility in 298 military basic trainees, with a mean value of 41.7 ± 8.3 degrees from full extension reported.

The present study did produce results similar to those reported by Hennessey & Watson (1993), who compared the PKE flexibility between hamstring injured and non-injured professional rugby and Gaelic football players. The authors reported mean PKE values of 11.9 ± 11.1 and 12.5 ± 8.1 degrees from full extension for the injured and uninjured limbs of the Injured group (N = 18), and values of 14.1 ± 9.7 and 11.7 ± 9.4 degrees from full extension for the left and right limbs of the Non-injured group (N = 16).

Differences in the values of PKE in the present study compared to those reported in the literature may be due to differences in knee joint angle determination, the use of video analysis in present study and goniometry in referred studies, or differences in study population. The latter seems more likely due to the similarities in study populations and results from the present study and the findings of Hennessey & Watson (1993).

Passive Peak Torque

Passive peak torque is the maximum amount of resistance (Nm) offered by the hamstrings in response to passive stretch. Passive peak torque occurs at the end range of motion of a stretch manoeuvre and represents the stretch tolerance of the subject, or the maximum tension in the tissue allowed by the subject (Magnusson, 1998). The mean passive peak torque values for the Injured and Non-injured groups ranged from 38.8 ± 7.5 Nm to 46.4 ± 10.4 Nm (Table 4-3) and were similar to other passive peak torque values reported in the literature.

Magnusson et al (1995a) reported a mean value of 44.0 ± 3.9 Nm for the peak torque in 10 normal subjects, while Magnusson et al (1996b) reported a mean torque value of 42.8 ± 3.7 Nm in a study of 13 normal subjects. A study by Gajdosik et al (1990) found a mean peak torque value of 41.4 ± 5.7 Nm during passive extension of the knee in 15 healthy male subjects. A study of eight healthy male subjects by Magnusson et al (1996d) reported a mean passive peak torque of 34.2 ± 3.8 Nm. In a study comparing male subjects involved in either a strength or a strength and flexibility program, Klinge et al (1997) reported passive peak torque values of 34.6 ± 9.8 Nm and 23.1 ± 6.3 Nm, respectively.

The fact that the values for passive peak torque were similar to those reported in the literature suggests that the method of determining passive peak torque used in the present study was valid.

Angle at Passive Peak Torque

Angle at passive peak torque refers to the angle of the knee at which the subject attains peak torque in response to passive stretch of the hamstrings. The angle at passive peak torque is always the angle closest to full extension of the knee and is directly related to the range of motion about the joint (Magnusson, 1998). The more range of motion about the knee that a subject has, the closer to full extension their knee will be during passive stretch on the Kin/Com dynamometer.

Mean angles at passive peak torque for the injured and uninjured limbs of the Injured group were 8.9 ± 7.1 and 10.3 ± 8.2 degrees from full extension. For the Non-injured group, the mean angles at peak torque were 8.4 ± 8.9 and 10.9 ± 5.5 degrees from full extension for the matched injured and uninjured limbs, respectively. These values demonstrate greater range of motion than those values reported in the literature. In a study of 15 healthy male subjects, Gajdosik et al (1990) reported a mean maximum knee angle at peak torque of 18.9 ± 7.9 degrees from full extension during passive extension of the knee with the hip flexed at approximately 90 degrees.

The difference in these values and the present study may be due to measurement of the knee joint angle using the two different methods. Gajdosik et al (1990) measured the knee angle directly using photography whereas measurement of the knee joint angle in the present study was based on the assumption that the angle of the knee was equal to the angle of the actuator arm of the Kin/Com dynamometer. However, a small difference exists between the angle of the knee joint and the angle of the dynamometer actuator arm (Herzog, 1988). This is due to the fact that the instantaneous axis of rotation of the knee changes position as the knee moves from a position of flexion into extension (Nordin & Frankel, 1989), while the axis of rotation of the dynamometer actuator arm remains constant. Therefore, the angle at passive peak torque, as measured by the Kin/Com Dynamometer, may not be an exact representation of the knee joint angle. Herzog (1988) reported that the angle of the dynamometer actuator arm and the angle of the shank (leg), relative to the vertical, were similar during isokinetic movements of the knee, but the angle of the actuator arm was always slightly larger. Therefore, the Kin/Com may slightly overestimate the range of motion of the leg about the knee. This error can be minimized and considered negligible if proper subject stabilization methods are employed (Herzog, 1988).

Comparison of angle at passive peak torque values from the present study to those reported by Magnusson and colleagues is inappropriate due to the difference in hip joint position used in the two methods. The present study placed the hip in a position of approximately 90 degrees during the Kin/Com test. The method employed by Magnusson and colleagues (1995-2000) employed a hip flexion angle of 110 to 135 degrees from anatomical position (more hip flexion than the present study). The hamstrings cross both the hip and knee and are stretched by both hip flexion and knee extension. Therefore, the position of increased hip flexion would place a greater stretch on the hamstrings and thus reduce the magnitude of joint range of motion about the knee during extension. This difference would not translate to measures of peak torque or stiffness as the length of the hamstrings during stretch in the different positions should not change, although this has not as yet been investigated.

Maximal Stiffness

Maximal stiffness refers to the rate of change of tension within the muscle during the final 10 degrees of passive stretch, as noted by the slope of the passive torque-angle curve for the muscle (Figure 5-1). The method used to calculate stiffness in this study, outlined in Chapter 3, involves dividing the change in passive torque by the change in joint angle. This method is simple to use but is only valid if the graph is linear (Hall, 1999). Because the portion of the graphs being evaluated were fairly linear, this method was considered to be a valid measure of stiffness. An improvement to this method would be to smooth the graph mathematically and calculate the slope using integration.

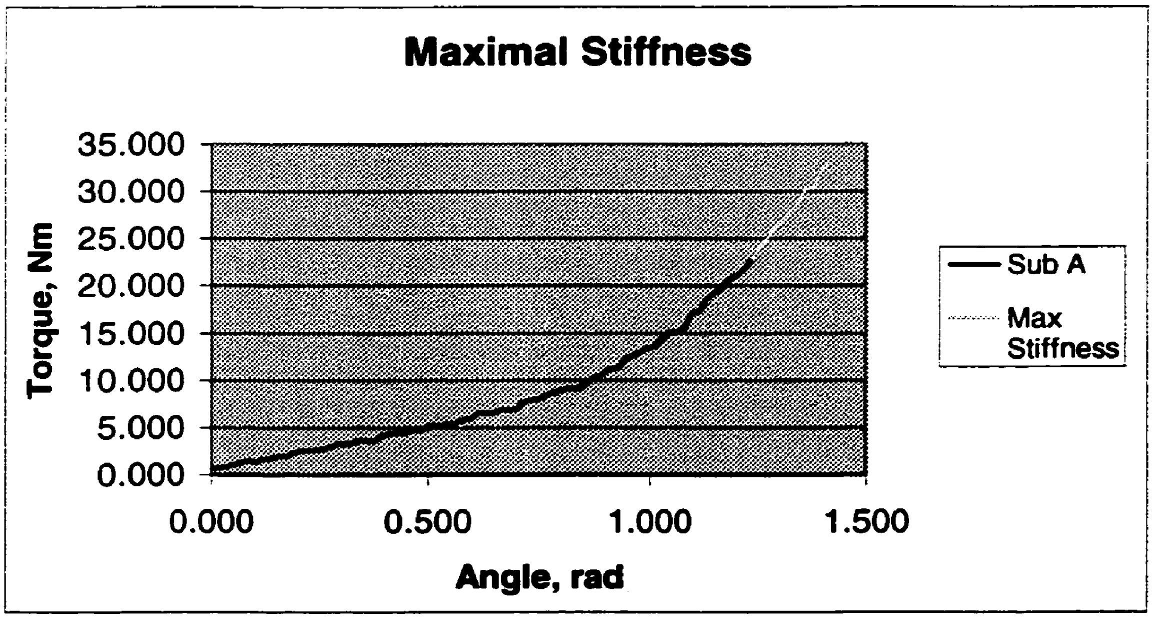


Figure 5-1. Determination of maximal stiffness from a torque-angle curve. The slope of the torque-angle curve in the final 10 degrees for Sub A is 59.064 Nm/rad.

The values for maximal stiffness reported in the present study (Table 4-3) were higher than those values reported by Magnusson et al (1995a), Magnusson et al (1996b), and Magnusson et al (1997), which were 30.2 ± 3.2 Nm/rad, 47.7 ± 4.2 Nm/rad, and 28.0 ± 2.9 Nm/rad & 54.9 ± 6.5 Nm/rad, respectively. This finding can be attributed to the fact that all subjects in the present study were participating in a strength program, which has been shown to cause an increase in maximal stiffness (Klinge et al, 1997; Magnusson et al, 1997). It has been proposed that the muscle hypertrophy commonly associated with strength training may be responsible for the increase in maximal stiffness (Klinge et al, 1997; Magnusson et al, 1997). The increase in muscle cross-sectional area due to increased muscle fibre size and connective tissue means that there would be more muscle tissue involved in the stretch. Therefore, someone with a larger cross-sectional area of the hamstrings should have a higher stiffness during stretch, although this relationship has not yet been extensively investigated (Gajdosik et al, 1990; Klinge et al, 1997).

The higher stiffness values may also be due to the differences in study populations. Most of the studies in the literature used normal subjects or recreational athletes, whereas the present study examined elite athletes involved in sprinting activities and heavy weight-training regimes. This would support the hypothesis that an athlete with a greater cross-sectional area would have a stiffer muscle, but again this has not been investigated.

Clinical Tests Vs. Kin/Com Test Comparison

The primary reason for comparing these three clinical tests and the resistance offered by the knee flexors during passive extension of the knee is that this comparison has not been investigated in the literature. Also, this study was performed to investigate the use of the Kin/Com Isokinetic Dynamometer as measure of hamstring flexibility and resistance to stretch, in an effort to provide more information to patients on the rehabilitation of hamstring muscle strains. The three clinical tests are used to measure range of motion changes during rehabilitation. The angle at passive peak torque can also be used to measure improvements in range of motion about the knee. The other Kin/Com variables (passive peak torque and stiffness) could be used to measure improvements in stretch tolerance and muscle consistency.

Sit and Reach Test Vs. Kin/Com Test

Comparison of Sit and Reach Test (SR) scores to the variables of the Kin/Com Test revealed several significant relationships. A higher score in the SR test was related to a lower angle at peak torque (i.e. angle closer to full extension), or a greater range of motion at the knee joint. This result is similar to that reported by Jackson and Langford (1989) who found that a greater SR test score was significantly related to greater hamstring flexibility, as measured during a passive straight leg raise.

The SR test was also significantly related to maximal stiffness, with a higher SR score relating to a higher maximal stiffness, which is the slope of the passive torque-angle curve in the final degrees of extension during a stretch maneuver. The maximal stiffness refers to the rate of increase in tension in the hamstrings during the final degrees of knee extension. Subjects that have a greater range of motion about the knee during stretch will have a greater stiffness in the hamstrings. This finding is supported by Magnusson et al (1997), who reported that athletes with the ability to reach beyond their toes during a toe touch movement had a greater maximal stiffness than those athletes that could not reach their toes. The authors attributed this difference to a greater tolerance to stretch in the hamstrings in those athletes with better flexibility. Magnusson et al (1997) defined the tolerance to stretch as the ability of the subject to allow greater forces to be developed within the tissue during a stretch maneuver. Although the SR test is not limited to hamstring flexibility, it is related to hamstring flexibility and thus subjects with greater hamstring flexibility and tolerance to stretch should perform better on the SR test than someone with less flexibility. Other joints that may affect SR scores include the lower back, the upper back, and the shoulder girdle.

The SR test was also significantly related to the common stiffness, which is the stiffness of the tissue in a range of motion common to all subjects as determined by the slope of the passive torque-angle curves. Subjects with a higher SR test score had a lower common stiffness, or a lower slope to the torque-angle curve. Reasons for this significant relationship are similar to that of the SR-maximal stiffness relationship. Subjects with greater flexibility take longer to develop tension in the tissue during passive stretch, as seen on a passive torque-angle curve. The curves are similar in shape but the T-A curve for Subject B is shifted to the right of the curve for Subject A, a result of the increased range of motion for Subject B. Because of this apparent shift, the slope of the T-A curve for Subject B will be lower than that of Subject A within the same range of motion. There was no significant relationship between the SR score and the peak passive torque value.

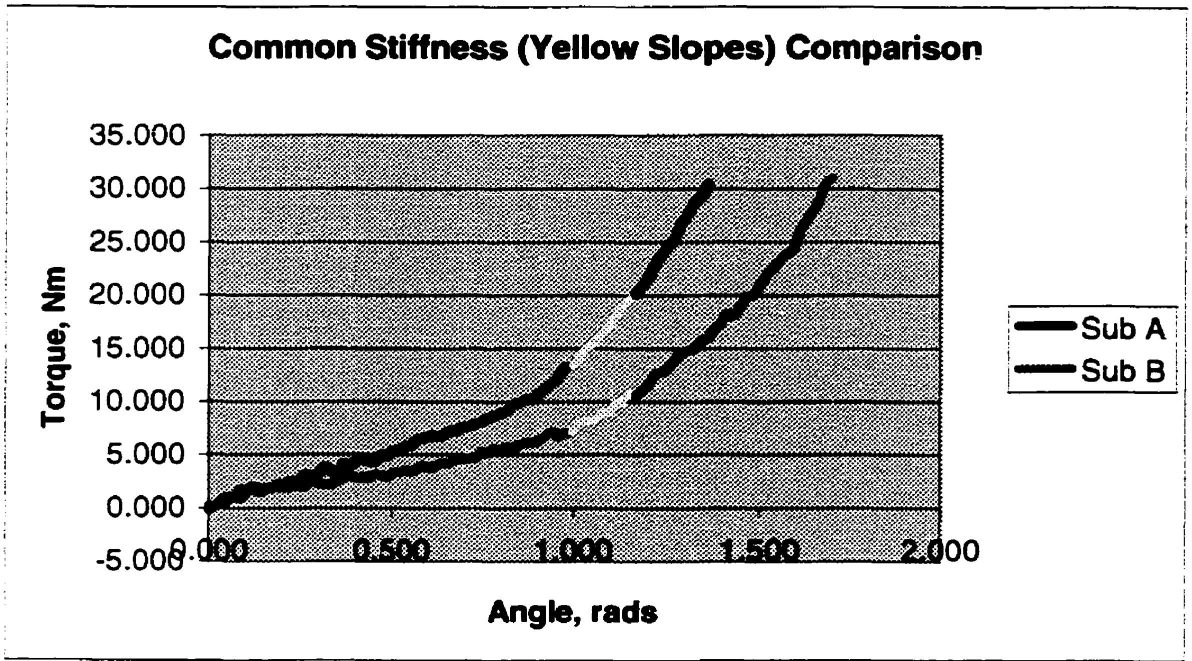


Figure 5-2. Passive torque-angle comparison between normal subjects with differing flexibility (Sub B > Sub A). Common stiffness (yellow slopes) values are 38.425 Nm/rad for Sub A and 19.510 Nm/rad for Sub B.

Active Knee Extension Test Vs. Kin/Com Test

Results from the study indicate that the Active Knee Extension Test (AKE) was significantly correlated to the angle at peak torque and the common stiffness. A lower AKE score was related to a smaller angle at peak torque. Both scores relate to a greater range of motion about the knee joint. A lower AKE score was also related to a lower common stiffness. This correlation can be attributed to the curvilinear nature of passive torque/angle relationship. As the subject extended his knee towards the end range of motion, there was an increase in the passive resistance (torque) about the knee. This increase occurred more rapidly in subjects with less range of motion, as compared to subjects with greater range of motion. In a comparison of torque/angle graphs between subjects, as seen in Figure 5-2, the subject with a greater range of motion (Subject B) would have a lower slope and therefore a lower common stiffness within the same range of motion. This is due to the observation that subjects with a greater flexibility will take longer to develop tension within the tissue during passive stretch within a given range of motion.

Although there were no studies in the literature relating Active Knee Extension to the resistance to stretch during passive extension of the knee, this relationship can be attributed to the curvilinear response to stretch. A subject with a large active range of motion about the knee joint will have a greater range of motion and therefore take longer to develop tension within the tissue during passive stretch.

Passive Knee Extension Test Vs. Kin/Com Test

The results from the Passive Knee Extension Test (PKE) show significant relationships with the angle at peak torque and stiffness in a common range. A lower score on the PKE test corresponded to a lower angle at peak torque. This highly significant relationship is logical as both tests are measuring the passive range of motion toward extension about the knee with the hip in a position of approximately 90 degrees of flexion. Another similarity is the slow angular velocities about the knee joint during both tests.

Two differences between the two tests were in the determination of the end point for each trial and the method by which the leg was moved about the knee. The end point for the PKE test was determined during each trial, and therefore, separately for each trial of the test, whereas the end point during the Kin/Com test was predetermined before the test trials and the same end point was used for each trial. During the PKE test, the examiner moved the subject's leg, whereas the leg was moved by the dynamometer during the Kin/Com test. These subtle differences appeared to have no effect on the results, as noted by the strong correlation between the two tests. Thus, the validity of the Kin/Com test to measure passive range of motion about the knee during a stretch manoeuvre was verified.

A lower PKE test score was also related to a lower common stiffness, which would be attributed to the same reasons as the Active Knee Extension Test – common stiffness relationship. A subject with greater flexibility in the hamstrings will take longer to develop the same tension in the tissue than a person with poor flexibility, and therefore the rate of change in tension is lower within the same range of motion. However, there were no studies in the literature reporting the relationship between the Passive Knee Extension Test and the resistance to stretch during passive extension of the knee as measured by an isokinetic dynamometer.

Injured Group Vs. Non-injured Group Comparison

This comparison was performed to detect differences in flexibility variables between hamstring-injured and non-injured subjects and to evaluate the Kin/Com Isokinetic Dynamometer as a measurement tool for determining hamstring strain injury healing progress. The results of this study show only a few significant differences in the different test variables between hamstring injured and non-injured subjects. However, more differences would be expected since injured muscles usually contain increased scar tissue (Garrett, 1996). The presence of inelastic scar tissue may cause an increased stiffness within the tissue, resulting in a decreased range of motion about the joint (Nikolaous et al, 1987). The lack of a large number of significant results may be indicative of careful rehabilitation and return to activity progressions (Hennessey & Watson, 1993; Andrews et al, 1998).

Sit and Reach Test

There was no significant difference in Sit and Reach scores between injured and non-injured subject groups. This finding supports research performed by Burkett (1970), Stephens & Reid (1988), and Orchard et al (1997), who examined the differences in Sit and Reach scores between hamstring injured and non-injured professional football players. The lack of a significant difference between the two groups was attributed to the fact that the Sit and Reach test is a general, multi-joint flexibility test, meaning that the outcome of the test is dependent on the range of motion about the knee, hip, spine, shoulder girdle and upper extremities (Burkett, 1970; Stephens & Reid, 1988; Orchard et al, 1997). Thus, if there was a difference in hamstring flexibility present between the two groups, it may be masked by an increased flexibility in the leg and ankle, the lower and upper back, or the shoulder girdle, or by differences in limb lengths (Jackson & Langford, 1989; Knapik et al, 1992; Worrell & Perrin, 1992).

Also, the differentiation between injured and uninjured limbs cannot be made because the Sit and Reach Test is a bilateral measure of flexibility, as noted by Hennessey & Watson (1993). By this rationale, it is possible that the SR scores are limited by the flexibility of the injured limb, which may be less than the uninjured leg. If this was true, the lack of significant differences in SR scores in the literature only confirms the notion that the SR test is not specific enough to detect hamstring flexibility differences between injured and non-injured athletes.

Active Knee Extension Test

The results of the study show significant differences in Active Knee Extension (AKE) test range of motion between the injured and non-injured groups. In a comparison between injured group and non-injured group injured limbs, and the injured group vs. non-injured group uninjured limbs, the injured group scores were significantly higher than the non-injured group scores in both cases. Also, the injured limb values for the injured group were significantly higher than the uninjured limb values for the non-injured group. Lower scores in the AKE test, measured in degrees from full extension, indicated greater knee extension and, thus, increased hamstring flexibility. Therefore, the Injured group subjects were significantly less flexible than the Non-injured group.

These results are not consistent with those of Bruce (1989) who found no significant differences in Active Knee Extension scores between hamstring injured and non-injured groups. The author attributed these results to full rehabilitation of the injured limb (Bruce, 1989). The discrepancy between these results and the results of the present study may be due to different methods of flexibility measurement (flexometer vs. video analysis) and/or different sample populations. This discrepancy and lack of studies on this topic suggest the need for further investigation to clarify the relationship between active knee flexibility and previous strain injury.

There was no significant difference in Active Knee Extension Test scores between limbs within injury groups, which support the findings of Bruce (1989). Again the author attributed the lack of a difference to full rehabilitation following injury (Bruce, 1989).

It has been suggested in the literature that the Active Knee Extension Test is a measure of initial or un-stretched hamstring length, with the end range of motion indicating the point of initial resistance within the muscle (Gajdosik et al, 1983; Gajdosik et al, 1993). A decrease in active range of motion during knee extension can be attributed to a shortened hamstring muscle length or a decrease in the subject's tolerance to stretch (Gajdosik et al, 1993), meaning that there is a decrease in the amount of tension the subject will allow to develop within the tissue before stopping the movement due to pain or discomfort. By this rationale, subjects who had sustained a hamstring injury had a decrease in tolerance to stretch, as compared to healthy subjects. It is uncertain whether a decreased stretch tolerance was a pre-injury condition, or occurred as a result of hamstring injury. If the former situation were true, then it may be possible to pre-screen athletes for the likelihood of sustaining a hamstring strain injury. However, pre-screening of athletes has been inconclusive (Hennessey & Watson, 1993; Orchard et al, 1997; Bennell et al, 1998). A prospective study by Orchard et al (1997) looked at the incidence of hamstring strain injury in 37 professional footballers and found that those athletes that sustained injury had weaker hamstrings in the injured leg than in the opposite leg. This result was not supported by Bennell et al (1998), who concluded that pre-season isokinetic strength testing was not able to predict hamstring strain injury in

102 professional footballers. In a retrospective study, Paton et al (1989) found no significant differences in isokinetic strength between previously injured athletes and athletes with no history of injury. Pre-season flexibility testing using either the Sit and Reach test (Orchard et al, 1997) or the Passive Knee Extension test (Hennessey & Watson, 1993) was not able to predict hamstring injury.

If the injury produces decreased flexibility, it may be attributed to changes in the consistency of the muscle tissue around the site of injury, such as a decrease in tissue pliability due to the formation of an inelastic scar within the tissue (Nikolaous et al, 1987). Investigations into the effectiveness of different treatment interventions on hamstring strain injury should then be performed to determine the best method for reducing this increased tissue stiffness.

Passive Knee Extension Test

No significant differences between injured and non-injured groups were noted during the Passive Knee Extension Test. There were also no significant differences in Passive Knee Extension Test scores found between injured and uninjured limbs within either the hamstring injured or non-injured groups. These results were similar to the findings of Hennessey & Watson (1993) who found no significant differences in passive knee extension scores between the injured and uninjured limbs of hamstring injured and non-injured athletes. The authors attributed this lack of a difference to careful attention to stretching during rehabilitation of the injured athlete (Hennessey & Watson, 1993). It is possible that the results of the present study can be attributed to careful rehabilitation, but the details of the rehabilitation programs for the subjects in the present study were not known.

The results of this study were not consistent with the findings of Worrell et al (1991) and Jonhagen et al (1994), who also examined the differences in passive flexibility between hamstring injured and non-injured athletes. Worrell et al (1991) found significantly higher passive knee extension scores in the injured limbs of injured athletes, as compared to their uninjured limbs and the limbs of non-injured control group subjects. A study by Jonhagen et al (1994) examined differences in hamstring flexibility between injured and non-injured sprinters using the passive straight leg raise test. Results suggested significantly less hamstring flexibility in the injured group as compared to the non-injured group. The authors attributed their findings to changes in the muscle consistency due to scar formation within the tissue, resulting in decreased tolerance to stretch for that limb (Worrell et al, 1991; Jonhagen et al, 1994). This is supported by Taylor et al (1993), who found that prior injury makes muscle more susceptible to a second injury in in vitro studies in rabbits. Specifically, the authors found that rupture in rabbit skeletal muscle with a previous strain injury required 63% of the load required to rupture healthy control muscle, and the length at rupture was 79% of the control length at rupture. The results of the present study suggest that the presence of any scar tissue within the muscles of the injured group limbs was not enough cause a decrease in stretch tolerance during the PKE test, as compared to the Non-injured group.

A limitation of the Passive Knee Extension Test is that subjects who could fully extend their knee with their hip in 90 degrees of flexion may not feel a stretch in this position. Some subjects in the present study reported this phenomenon with the Passive Knee Extension Test. A modification to reduce the incidence of this limitation was suggested by Fredriksen et al (1997). This study examined the reliability of a passive knee extension test with the hip stabilized in a flexion angle of 120 degrees from anatomical position, instead of the 90 degrees of hip flexion normally employed. A standardized force, 68.7 N as measured by a hand held force transducer, was also used to extend the leg. The authors reported an intraclass coefficient of 0.99 with a test-retest protocol. Implementation of this protocol in future studies may help to demonstrate a significant difference in Passive Knee Extension scores between injured and non-injured groups.

Limitations in the use of the method proposed by Fredriksen et al (1997) do exist, however. Because this method is not widely reported, there is very little information in the literature to which results can be compared. This limitation may only be temporary if more PKE values are reported using this method. Another limitation of this method is that it required two testers to perform, one to move the leg and one to measure the knee angle with a goniometer. This may be overcome with the use of video analysis to determine the knee joint angle, or the use of a cradle to maintain hip position of 120 degrees of flexion.

Passive Peak Torque

Results from the study indicate no significant differences in passive peak torque values between the injured and non-injured groups. There was a trend ($p = 0.08$) for the passive peak torque of injured limbs in the injured group subjects to be greater than the passive peak torque of the uninjured limbs in the non-injured group subjects, but this difference was not significant at $p < 0.05$. This difference may have become significant if more subjects were added to the study. There were no studies in the literature reporting on differences in peak torque between hamstring injured and non-injured subjects. The potential differences may be due to individual differences in muscle fibre composition and cross-sectional area, or differences in individual tolerance and comfort level with the amount of tension developed within the tissue.

Angle at Peak Torque

There were no significant differences in the angle at peak torque found between the injured and non-injured groups. Although there were no studies located in the literature directly related to this particular comparison, this finding may be related to lack of a significant difference in PKE Test values noted between the two groups in the present study, as both variables are strongly correlated and relate to the passive joint range of motion about the knee.

Maximal Stiffness

The results of the study show significant differences in the maximal stiffness values of the injured limbs and uninjured limbs between the injured and non-injured groups. The maximal stiffness values of the injured and uninjured limbs of the injured groups were significantly higher than those for the non-injured group. Also, the injured limbs of the injured group had a significantly higher maximal stiffness than the uninjured limbs of the non-injured group. Wilson et al (1991) argued that increased stiffness in the musculature increases the potential for injury due because the musculotendinous unit must absorb energy more rapidly or in a shorter range of motion, thus increasing the likelihood of failure. Increased stiffness in injured muscles has been attributed to adhesions within the muscle (Garrett et al, 1987; Safran et al, 1988) and even calcification within the muscle tissue (Garrett et al, 1989).

In response to strain injury, there is haemorrhage within the tissue, denoted as the inflammatory phase (Andrews, Harrelson, & Wilk, 1998). Fibre disruption is along the myotendinous junction, located throughout the length of the hamstring muscle (Garrett et al, 1987), and there is a significant loss of contractile ability during this phase (Nikolaous et al, 1987). After a few days, depending on the severity of the injury, the haemorrhaging stops and the muscle enters the repair phase, characterized by a reduction in edema and formation of a collagen matrix to form a union at the site of fibre disruption (Arnheim & Prentice, 1991; Andrews, Harrelson, & Wilk, 1998). The contractile ability of the muscle begins to slowly return back to normal. By day 7, full function is almost restored as the contractile ability has reach 92% of pre-injury levels and the visible edema has disappeared (Nikolaous et al, 1987). At this point, the muscle is still very susceptible to injury. Taylor et al, (1993) reported that failure of rabbit muscle in this state of healing required only 63% of the load needed to fail normal controls, and the length at rupture was 79% of controls. This has been attributed to the formation an inelastic scar at the site of fibre disruption. This is the weak point in the muscle, as failure occurs within or directly adjacent to this scar (Nikolaous et al, 1987; Taylor et al, 1993). The tissue must undergo a lengthy remodelling phase in order to demonstrate elasticity similar to non-injured muscle, although the muscle may never return to normal (Safran et al, 1988;

Garrett et al, 1989). Therefore, the tissue may retain an increased stiffness following injury.

Common Stiffness

The results from this comparison indicate no significant difference in stiffness in a common range of motion between Injured and Non-injured groups. There were no studies found in the literature directly relating to this topic. The present result may be related to the lack of a significant difference in the angle at peak torque, which is the indication of the range of motion during passive extension of the knee with the Kin/Com Test. Magnusson et al (1997) noted significant differences in common stiffness between individuals with tight hamstrings and individuals with normal flexibility, with subjects possessing greater flexibility having a lower common stiffness. All subjects had similar ranges of motion during the Kin/Com test, and therefore, should present a similar stiffness in a common range of motion. This result suggests that stiffness before the final degrees in the range of motion are not as relevant to hamstring injuries as the maximal stiffness. This is supported by the fact that hamstring muscle strain injuries occur during movements within the end ranges of motion of the knee joint (Garrett, 1996).

Summary of Discussion

This study was performed to determine the relationship of three clinical flexibility tests to the passive properties of the hamstrings during a stretch maneuvre. In addition, the differences between hamstring injured and non-injured subjects were compared. Significant differences in maximal stiffness between the groups suggest that hamstring injured athletes have stiffer hamstrings at the end range of motion, which may indicate incomplete rehabilitation. Athletes with stiffer hamstrings may be pre-disposed to injury because of a sharper rise in tension within the muscle tissue (Klinge et al, 1997). The present information about muscle stiffness after injury may assist the rehabilitation specialist in determining full rehabilitation and/or determine the best method of treatment to reduce the risk of re-injury.

Chapter 6

Summary, Conclusions, and Recommendations

Summary

The high incidence of recurrent hamstring injuries in sport, especially in the recent Summer Olympics, calls into question the accuracy of current measures of injury rehabilitation. Strength and flexibility differences between healthy and previously hamstring-injured athletes have been reported in the literature, but many studies have found no significant differences between the two groups using similar testing methods. Studies of the passive properties of skeletal muscle have measured the resistance to passive knee extension using a Kin/Com isokinetic dynamometer. Comparison of this flexibility measurement technique to other, more common measures of flexibility is not well documented in the literature. Also, there is little information in the literature with respect to the passive properties of in vivo skeletal muscle with a previous strain injury

The purpose of this study was to compare the measurement of knee flexor (hamstring) flexibility by use of three clinical tests, the Sit and ReachTest, Active Knee Extension Test, and Passive Knee Extension Test, to the resistance to stretch as measured by the Kin/Com Isokinetic Dynamometer during passive extension of the knee. A sub-problem was to examine the differences in flexibility measurement scores between individuals with a previous hamstring strain injury and individuals with no history of strain injury.

Twenty male elite athletes were recruited from the University of Manitoba Varsity Football and Track teams. Non-injured subjects (N=10) were matched with

Injured subjects (N=10) according to sport, position, weight, height and limb dominance. The Non-injured group limbs were separated into 'injured' and 'uninjured' groups according to the injured and uninjured limbs of their Injured group counterparts. Data collection and comparisons were made on the Sit and Reach Test scores, the Active Knee Extension Test scores, and the Passive Knee Extension Test scores, as well as the variables of passive peak torque, angle at passive peak torque, maximal stiffness, and stiffness in a common range.

Regression analysis between the three clinical tests and the resistance to stretch variables resulted in several significant correlations. The Sit and Reach Test was significantly related to the angle at passive peak torque, maximal stiffness, and common stiffness ($p < 0.05$). Both the Active Knee Extension Test and the Passive Knee Extension Test were significantly related to the angle at passive peak torque and common stiffness values ($p < 0.05$). These results suggest that the Kin/Com Isokinetic Dynamometer is a valid measure of hamstring flexibility.

Two-way analyses of variance (ANOVA) with one between subjects factor (group) and one within subjects factor (limb) were performed for each of the clinical flexibility test scores and the Kin/Com variables. Injured athletes had significantly less flexibility in both limbs than the Non-injured athletes, as measured by the Active Knee Extension Test ($p < 0.05$). Injured athletes also had significantly greater maximal stiffness in both limbs, as compared to the Non-injured athletes. Injured athletes also had significantly higher stiffness in the final range passive extension of the knee in both limbs than the Non-injured group ($p < 0.05$). These results suggest that the Injured athletes may be at greater risk of strain injury than normal, Non-injured athletes, as the higher stiffness may be indicative of the presence of scar tissue within the muscle. Therefore, therapists need to continue efforts to decrease scar tissue and stiffness in the hamstring even after the athlete has returned to full activity in order to reduce the risk of re-injury. There were no other significant differences between the groups.

The results of the present study suggest that the Kin/Com Isokinetic Dynamometer would be a valuable tool for determining the flexibility and stiffness of the hamstrings following strain injury.

Conclusions

1) Greater flexibility, as measured by the Sit and Reach, Active Knee Extension, and Passive Knee Extension tests, was significantly correlated to a greater range of motion during passive extension of the knee with the Kin/Com Isokinetic Dynamometer. All of the tests may be considered to be valid methods of evaluating hamstring flexibility.

2) There were no significant correlations between flexibility, as measured by the Sit and Reach, Active Knee Extension, and Passive Knee Extension tests, and the peak passive torque or maximal stiffness of the hamstrings measured by the Kin/Com Isokinetic Dynamometer during passive extension of the knee. Clinical measurement of hamstring flexibility appears to be unrelated to peak passive torque or maximal stiffness of the hamstrings.

3) There was a significant difference in the Active Knee Extension Test scores, which were significantly higher in the injured and uninjured limbs of the hamstring Injured athletes as compared to the injured and uninjured limbs of the Non-injured control group. Hamstring injured subjects appear to have less flexibility during active movements than subjects without hamstring strain injuries.

4) The maximal stiffness values in the injured and uninjured limbs of the Injured group were significantly higher than the injured and uninjured limbs of the Non-injured control group. Hamstring injured subjects appear to have greater stiffness in the hamstrings during the final degrees of passive extension of the knee.

5) There were no significant differences in Sit and Reach scores or Passive Knee Extension scores between Injured and Non-injured subject groups or between injured and

un-injured limbs within subjects. Flexibility measurement by the Sit and Reach and Passive Knee Extension tests appears to be unaffected by hamstring strain injury.

6) There was no significant difference in passive peak torque values between Injured and Non-injured subject groups.

Recommendations

The following recommendations have been made based on the current study and may be of benefit to other researchers planning to conduct similar investigations.

1) Research should continue to examine the relationships between different clinical tests of hamstring flexibility and the resistance to stretch offered by the knee flexors during passive extension of the knee, as there is very little information about this topic reported in the literature. This will function to clarify the relationships between the Clinical tests of flexibility and the peak torque and maximal stiffness of the hamstrings during passive extension of the knee.

2) Further research is needed to examine differences in flexibility and resistance to stretch between hamstring injured and non-injured subjects. Preseason testing could provide researchers with a database of flexibility parameters and would provide the opportunity for comparison to pre-injury levels should an athlete sustain a hamstring strain injury in-season (prospective study).

3) Investigations into the effects of different methods of rehabilitation on the stiffness of the hamstrings following hamstring strain injury should be made. By determining the most effective method(s) by which to rehabilitate the injured athlete, it may be possible to reduce the risk of re-injury when the athlete returns to competition.

4) A larger sample population is recommended. Although some significant differences were found between Injured and Non-injured subjects, there were trends in the data that were not of statistical significance. A larger sample size may lead to more significant findings.

5) Studies incorporating different study populations, such as female athletes and athletes from different sports, should be performed. This may help clarify differences between Injured and Non-injured athletes and allow for more generalization of the results.

6) Research should investigate the relationship between muscle strength and the resistance to stretch as measured by a Kin/Com Isokinetic Dynamometer, as this has not been well documented in the literature.

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Appendix A

Example of an Adult Informed Consent signed by all participants.

Adult Informed Consent

You have volunteered to participate in a study entitled "Flexibility Measurement of the Knee Flexors: A Comparison of Three Clinical Tests and Isokinetic Dynamometry". This study is a topic of a master's thesis being completed by the Investigator, Stephen Diakow, a graduate student in the Faculty of Physical Education and Recreation Studies.

You have been asked to participate in this study because you fall into one of two categories: (1) you are an athlete who has sustained a unilateral hamstring muscle injury within the past 18 months, or (2) you are an athlete who has never sustained a hamstring injury. Participants from the injury group will be placed in the experimental group and those from the non-injury group will be placed in the control group. Both groups will perform the same test protocols.

There are two sets of requirements for this study, each corresponding to the Experimental and Control groups. Requirements for the Experimental Group are that you have sustained a hamstring strain injury within the past 18 months, completed a rehabilitation program and have returned to your activity or sport. You are free of symptoms related to this injury, as well as lower leg, knee, hip, or back pain or injuries.

Requirements for the Control Group are that you have never sustained any posterior thigh injury and are actively participating in your activity or sport. You are healthy and are free from symptoms related to lower leg, knee, hip, or back pain or injuries.

In the present study you, being a healthy athlete and meeting the requirements of one of the two groups, will be placed in either the Experimental or Control Group. Your height, weight, and the lengths of both upper and lower legs will be recorded. You will be required to perform four static stretches of the knee flexor muscles, 30 seconds in duration each. You will be required to perform four different flexibility tests for your knee flexors. Your active knee-flexor flexibility will be assessed with the Sit and Reach and Active Knee Extension Tests, and your passive knee-flexor flexibility will be assessed by the Passive Knee Extension Test and by the Kin/Com Isokinetic Dynamometer. All of these tests will be completed in the same test session in the Biomechanics Lab at the University of Manitoba. This session should last approximately one hour. All of these tests will be recorded on video and subsequently analyzed for the sole purpose of measuring the angle of your knee joint.

Your participation in this study is completely voluntary and you are free to stop your participation and withdraw from the study at any time without any penalty. You are free to ask any questions of the investigator at any time and you will receive a clear and honest response. The investigator will record all information, however, your information and data will remain confidential and will be stored in a locked environment at the University of Manitoba. The recorded data will not be redistributed or used for any other purpose other than the present study. Your identity will not be revealed at any time without your written consent.

Do you have any questions at this time?
Should you have questions at a later date, please contact us at any time.

Stephen Diakow (Investigator)
307 Max Bell Centre
Health, Leisure and Human Performance Research Institute
The University of Manitoba
Phone: 474-6875

Dr. Marion Alexander (Advisor)
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Health, Leisure and Human Performance Research Institute
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Margaret Bowman
Human Ethics Secretariat
The University of Manitoba
Phone: 474-7122

I, ______________________________, have read the above information and understand the testing procedures, the risks involved, and I agree to participate. I understand that all gathered information will be treated with strict confidentiality and that I will not be identified personally when the results from the study are presented. I understand that I have the right to refuse to participate in any testing trial and I have the right to withdraw from the study at any time without repercussions.

______________________________   ______________
Signature of Investigator   Date

______________________________   ______________
Signature of Participant   Date

______________________________   ______________
Signature of Witness   Date

Appendix B

Example of Microsoft Excel™ sheet used for Dynamometry Data and Calculations

Legend

len,m	Length of the leg, in metres.
CM/L	Distance from the proximal of Centre of Mass of the leg.
swt/bw	Ratio of the weight of the leg to the total weight of the body.
BW, kg	Body weight, in kilograms.
BW, N	Body weight, in Newtons.
CM posn	Position of Centre of Mass of the leg, in metres from the proximal end of the leg.
Moment	Moment of the weight of the leg.
rep	Kin/Com Test repetition number.
point#	Sample point number from Kin/Com data readout.
angle	Actuator arm angle, in degrees, from Kin/Com data readout.
mom	Moment, in Newton metres, from the Kin/Com data readout.
avg mom	Average of the Moments of the three Kin/Com test repetitions.
leg ang	Angle of the leg, in degrees relative to the Horizontal.
mmw	Moment of the weight of the leg
rjm	Moment about the knee due to resistance of the knee flexors to passive stretch.
jt ang	Angle of the knee, in degrees from full extension (anatomical position).

sub c8									
file name	sdcr.018	thigh, m	0.44	len, m	CM/L	swt/bw	BW, kg	BW, N	CM	Moment
leg	r	ht, m	1.89	0.485	0.437	0.062	78.9	774.01	0.2119	10.13813
order	pads									

rep	point#	angle	mom	rep	point#	angle	mom	rep	point#	angle	mom	avg mom	leg ang	mmw	rjm	jt ang
1	5	190	-4.8	2	3045	190	-5.6	3	6085	190	-6	-5.467	99	-1.586	-3.881	
1	25	189	-3	2	3065	189	-4.5	3	6105	189	-5.2	-4.233	98	-1.411	-2.822	
1	45	188	-3	2	3085	188	-3.7	3	6125	188	-4.5	-3.733	97	-1.236	-2.498	
1	65	187	-2.6	2	3105	187	-3	3	6145	187	-3.7	-3.100	96	-1.060	-2.040	
1	85	186	-1.5	2	3125	186	-2.6	3	6165	186	-3	-2.367	95	-0.884	-1.483	
1	105	185	-1.5	2	3145	185	-1.8	3	6185	185	-2.6	-1.967	94	-0.707	-1.259	
1	125	184	-1.1	2	3165	184	-1.1	3	6205	184	-1.8	-1.333	93	-0.531	-0.803	
1	145	183	0	2	3185	183	-0.7	3	6225	183	-1.5	-0.733	92	-0.354	-0.380	
1	165	182	0.3	2	3205	182	-0.3	3	6245	182	-0.7	-0.233	91	-0.177	-0.056	
1	185	181	0.3	2	3225	181	0	3	6265	181	-0.3	0.000	90	0.000	0.000	
1	205	180	0.7	2	3245	180	0.3	3	6285	180	0.3	0.433	89	0.177	0.256	
1	225	179	1.1	2	3265	179	0.7	3	6305	179	0.7	0.833	88	0.354	0.480	
1	245	178	1.1	2	3285	178	0.7	3	6325	178	0.7	0.833	87	0.531	0.303	
1	265	177	2.2	2	3305	177	1.5	3	6345	177	1.1	1.600	86	0.707	0.893	
1	285	176	2.2	2	3325	176	1.5	3	6365	176	1.8	1.833	85	0.884	0.950	
1	305	175	2.6	2	3345	175	2.6	3	6385	175	2.2	2.467	84	1.060	1.407	105
1	325	174	3.3	2	3365	174	2.2	3	6405	174	2.2	2.567	83	1.236	1.331	104
1	345	173	3.3	2	3385	173	1.8	3	6425	173	2.6	2.567	82	1.411	1.156	103
1	365	172	3.3	2	3405	172	2.2	3	6445	172	3	2.833	81	1.586	1.247	102
1	385	171	4.1	2	3425	171	3.3	3	6465	171	3.3	3.567	80	1.760	1.806	101
1	405	170	4.5	2	3445	170	4.1	3	6485	170	4.1	4.233	79	1.934	2.299	100
1	425	169	4.1	2	3465	169	4.5	3	6505	169	4.5	4.367	78	2.108	2.259	99
1	445	168	4.8	2	3485	168	4.1	3	6525	168	4.8	4.567	77	2.281	2.286	98
1	465	167	5.6	2	3505	167	4.5	3	6545	167	4.8	4.967	76	2.453	2.514	97
1	485	166	5.2	2	3525	166	4.8	3	6565	166	4.8	4.933	75	2.624	2.309	96
1	505	165	5.6	2	3545	165	5.2	3	6585	165	5.2	5.333	74	2.794	2.539	95
1	525	164	6	2	3565	164	6	3	6605	164	4.5	5.500	73	2.964	2.536	94
1	545	163	6.3	2	3585	163	6.3	3	6625	163	5.2	5.933	72	3.133	2.800	93
1	565	162	6.7	2	3605	162	6.7	3	6645	162	6	6.467	71	3.301	3.166	92
1	585	161	6.7	2	3625	161	7.1	3	6665	161	6	6.600	70	3.467	3.133	91
1	605	160	7.5	2	3645	160	7.1	3	6685	160	6.3	6.967	69	3.633	3.333	90
1	625	159	7.5	2	3665	159	7.5	3	6705	159	6.7	7.233	68	3.798	3.436	89
1	645	158	8.2	2	3685	158	7.8	3	6725	158	7.1	7.700	67	3.961	3.739	88
1	665	157	7.8	2	3705	157	7.8	3	6745	157	7.5	7.700	66	4.124	3.576	87

1	685	156	8.2	2	3725	156	8.2	3	6765	156	7.8	8.067	65	4.285	3.782	86
1	705	155	9	2	3745	155	8.6	3	6785	155	7.8	8.467	64	4.444	4.022	85
1	725	154	9	2	3765	154	9	3	6805	154	8.2	8.733	63	4.603	4.131	84
1	745	153	10.5	2	3785	153	9.3	3	6825	153	8.6	9.467	62	4.760	4.707	83
1	765	152	9.7	2	3805	152	9.3	3	6845	152	8.6	9.200	61	4.915	4.285	82
1	785	151	10.1	2	3825	151	9.7	3	6865	151	9.3	9.700	60	5.069	4.631	81
1	805	150	10.5	2	3845	150	10.1	3	6885	150	9	9.867	59	5.222	4.645	80
1	825	149	10.8	2	3865	149	10.5	3	6905	149	9.3	10.200	58	5.372	4.828	79
1	845	148	11.6	2	3885	148	10.8	3	6925	148	9.3	10.567	57	5.522	5.045	78
1	865	147	11.2	2	3905	147	11.2	3	6945	147	10.1	10.833	56	5.669	5.164	77
1	885	146	11.6	2	3925	146	11.2	3	6965	146	10.5	11.100	55	5.815	5.285	76
1	905	145	12	2	3945	145	11.6	3	6985	145	10.5	11.367	54	5.959	5.408	75
1	925	144	11.6	2	3965	144	12	3	7005	144	10.8	11.467	53	6.101	5.365	74
1	945	143	12.3	2	3985	143	12	3	7025	143	11.2	11.833	52	6.242	5.592	73
1	965	142	12.3	2	4005	142	12	3	7045	142	12	12.100	51	6.380	5.720	72
1	985	141	12.7	2	4025	141	12.7	3	7065	141	12	12.467	50	6.517	5.950	71
1	1005	140	13.1	2	4045	140	13.1	3	7085	140	12.3	12.833	49	6.651	6.182	70
1	1025	139	13.8	2	4065	139	13.1	3	7105	139	13.1	13.333	48	6.784	6.550	69
1	1045	138	14.2	2	4085	138	13.5	3	7125	138	13.5	13.733	47	6.914	6.819	68
1	1065	137	14.2	2	4105	137	14.2	3	7145	137	14.2	14.200	46	7.043	7.157	67
1	1085	136	14.6	2	4125	136	14.2	3	7165	136	14.6	14.467	45	7.169	7.298	66
1	1105	135	15.3	2	4145	135	14.2	3	7185	135	14.2	14.567	44	7.293	7.274	65
1	1125	134	15.7	2	4165	134	15	3	7205	134	14.6	15.100	43	7.415	7.685	64
1	1145	133	15.7	2	4185	133	15.3	3	7225	133	15	15.333	42	7.534	7.799	63
1	1165	132	16.1	2	4205	132	15.3	3	7245	132	15.7	15.700	41	7.651	8.049	62
1	1185	131	16.5	2	4225	131	16.8	3	7265	131	15.7	16.333	40	7.766	8.567	61
1	1205	130	16.8	2	4245	130	16.5	3	7285	130	16.1	16.467	39	7.879	8.588	60
1	1225	129	17.6	2	4265	129	17.2	3	7305	129	16.5	17.100	38	7.989	9.111	59
1	1245	128	18.7	2	4285	128	17.2	3	7325	128	16.8	17.567	37	8.097	9.470	58
1	1265	127	19.1	2	4305	127	17.6	3	7345	127	17.6	18.100	36	8.202	9.898	57
1	1285	126	18.7	2	4325	126	17.6	3	7365	126	18	18.100	35	8.305	9.795	56
1	1305	125	19.1	2	4345	125	17.6	3	7385	125	19.1	18.600	34	8.405	10.195	55
1	1325	124	19.8	2	4365	124	18.7	3	7405	124	18.7	19.067	33	8.503	10.564	54
1	1345	123	20.2	2	4385	123	18.7	3	7425	123	19.5	19.467	32	8.598	10.869	53
1	1365	122	20.2	2	4405	122	19.5	3	7445	122	19.8	19.833	31	8.690	11.143	52
1	1385	121	21	2	4425	121	20.2	3	7465	121	20.2	20.467	30	8.780	11.687	51
1	1405	120	20.1	2	4445	120	19.8	3	7485	120	20.2	20.033	29	8.867	11.166	50
1	1425	119	21.3	2	4465	119	20.6	3	7505	119	21	20.967	28	8.951	12.015	49
1	1445	118	21.3	2	4485	118	21.3	3	7525	118	21	21.200	27	9.033	12.167	48
1	1465	117	22.1	2	4505	117	22.1	3	7545	117	22.1	22.100	26	9.112	12.988	47

1	1485	116	22.8	2	4525	116	22.8	3	7565	116	22.8	22.800	25	9.188	13.612	46
1	1505	115	23.6	2	4545	115	23.6	3	7585	115	22.8	23.333	24	9.262	14.072	45
1	1525	114	24.3	2	4565	114	24	3	7605	114	22.8	23.700	23	9.332	14.368	44
1	1545	113	24.7	2	4585	113	25.1	3	7625	113	24.3	24.700	22	9.400	15.300	43
1	1565	112	25.5	2	4605	112	25.8	3	7645	112	25.5	25.600	21	9.465	16.135	42
1	1585	111	26.6	2	4625	111	25.5	3	7665	111	25.1	25.733	20	9.527	16.207	41
1	1605	110	27.3	2	4645	110	27	3	7685	110	25.5	26.600	19	9.586	17.014	40
1	1625	109	28.1	2	4665	109	28.1	3	7705	109	26.2	27.467	18	9.642	17.825	39
1	1645	108	28.5	2	4685	108	28.1	3	7725	108	28.5	28.367	17	9.695	18.672	38
1	1665	107	29.6	2	4705	107	30	3	7745	107	28.1	29.233	16	9.745	19.488	37
1	1685	106	30.3	2	4725	106	30.3	3	7765	106	29.2	29.933	15	9.793	20.141	36
1	1705	105	30.7	2	4745	105	30.7	3	7785	105	29.6	30.333	14	9.837	20.496	35
1	1725	104	31.8	2	4765	104	31.8	3	7805	104	31.1	31.567	13	9.878	21.688	34
1	1745	103	33	2	4785	103	33.3	3	7825	103	33	33.100	12	9.917	23.183	33
1	1765	102	34.8	2	4805	102	34.1	3	7845	102	32.6	33.833	11	9.952	23.881	32
1	1785	101	35.6	2	4825	101	36	3	7865	101	33.3	34.967	10	9.984	24.983	31
1	1805	100	36.3	2	4845	100	37.1	3	7885	100	35.2	36.200	9	10.013	26.187	30
1	1825	99	36.7	2	4865	99	36.7	3	7905	99	36.3	36.567	8	10.039	26.527	29
1	1845	98	38.6	2	4885	98	38.2	3	7925	98	37.5	38.100	7	10.063	28.037	28
1	1865	97	40.1	2	4905	97	40.1	3	7945	97	38.6	39.600	6	10.083	29.517	27
1	1885	96	41.2	2	4925	96	40.5	3	7965	96	39.7	40.467	5	10.100	30.367	26
1	1905	95	42.3	2	4945	95	42	3	7985	95	40.8	41.700	4	10.113	31.587	25
1	1925	94	43.1	2	4965	94	42.7	3	8005	94	42	42.600	3	10.124	32.476	24
1	1945	93	44.2	2	4985	93	43.5	3	8025	93	43.1	43.600	2	10.132	33.468	23
1	1965	92	43.5	2	5005	92	45	3	8045	92	43.8	44.100	1	10.137	33.963	22

Appendix C

Raw Pilot Study Data

Raw Pilot Study Data

			trial 1	trial 2	trial 3	average		
	ake, deg	test 1	25	26	23	24.7	mass, kg	78.5
sub #1		test 2	18	17	17	17.3	leg len, m	0.445
	pke, deg	test 1	20	21	21	20.7	thigh len, m	0.395
		test 2	23	22	21	22	ht, m	1.75
	sar, cm	test 1	30	32	32	32		
		test 2	32	34	34	34		
	ake,deg	test 1	16	17	17	16.7	mass, kg	64.7
sub #2		test 2	14	13	14	13.7	leg len, m	0.424
	pke,deg	test 1	11	11	10	10.7	thigh len,m	0.413
		test 2	8	6	7	7	ht, m	1.67
	sar, cm	test 1	32	35	34	35		
		test 2	34	35	35	35		
	ake,deg	test 1	9	8	9	8.7	mass, kg	78.8
sub #3		test 2	9	9	8	8.7	leg len, m	0.436
	pke,deg	test 1	11	12	13	12	thigh len,m	0.4
		test 2	10	9	8	9	ht, m	1.75
	sar, cm	test 1	42	43	43	43		
		test 2	44	45	45	45		

ake: active knee extension in degrees from full extension (0 deg)
pke: passive knee extension in degrees from full extension (0 deg)
sar: sit and reach, in centimetres from toes (0 cm). Neg indicates inability to reach toes
leg len: length of leg (lat. fem. condyle to the distal tip of the lat. Malleolus)

Appendix D

Subject Information Sheet

Hamstring Injury Questionnaire

Subject Information Sheet

Date: ______________________________
Name: ____ Age: __________
Address: ____
Phone Number: ______________________________

CONTROL GROUP: ________ EXPERIMENTAL GROUP: ________

TEST ORDER: ____________________ LEG ORDER: __________

MEASUREMENTS:

Height (m): __________
Mass (kg): __________
Length of Thigh (m): Right __________ Left __________
Length of Shank (m): Right __________ Left __________

SIT AND REACH SCORES (cm):

Trial #1: __________
Trial #2: __________
Trial #3: __________

Average of two closest values: __________

ACTIVE KNEE EXTENSION SCORES (deg):

	R	L
Trial #1:	__________	__________
Trial #2:	__________	__________
Trial #3:	__________	__________

Average of two closest values: __________ __________

PASSIVE KNEE EXTENSION SCORES (deg):

	R	L
Trial #1:	__________	__________
Trial #2:	__________	__________
Trial #3:	__________	__________

Average of two closest values: __________ __________

Hamstring Flexibility Study
Injury Questionnaire

Subject # ____

Age: ______

1. What sport(s) are you currently involved in? (Include training period and frequency)
   eg. Track Mid-season 5x/week

____
____
____
____

2. Have you had a hamstring strain injury requiring some time away from your activity in the past 18 months? (circle) YES NO
If 'no', please skip to question # 6.

3. In which leg did you sustain a hamstring injury? (circle)
   RIGHT LEG LEFT LEG

4. How long were you away from full activity? (days)________________

5. Have you ever injured this leg before? (circle) YES NO
   If 'yes', please describe (# of times, date (m/y), time away from activity).
   eg. 1 time, 07/00, 12 days

____
____
____

6. Which is your preferred leg? (circle) RIGHT LEFT
   If you are unsure, check with researcher.

7. Are you currently involved in a regular hamstring flexibility program? YES NO
   If yes, please describe (stretches, frequency).eg. Modified hurdlers stretch, 3x/week

____
____

8. Are you currently involved in a regular, lower body weight-training program?
   YES NO
   If yes, please describe (exercises, frequency). eg. Squats/ Leg Press, 3x/week

____
____
____

Appendix E

Subject Demographics and Matching

Test and Leg Order Random Allocation

Subject Demographics and Matching

sub	age	wt (kg)	ht (m)	yrs comp	sport	pos'n	flex	strg	dom	inj leg	days	prev inj	match		inj leg	non leg	dom
c1	23	73.5	1.75	4	track	spr	y	y	r				e1	c1	r	l	r
c2	22	74.4	1.82	3	track	spr	n	y	r				e2	c6	r	l	r
c3	23	76.6	1.74	4	football	rb	n	y	l				e3	c8	r	l	r
c4	20	98	1.89	2	football	lb	n	y	r				e4	c3	l	r	l
c5	20	83.4	1.86	2	football	db	n	y	r				e5	c4	rl		r
c6	28	93.6	1.8	7	fb/track	rb/spr	y	y	r				e6	c10	r	l	r
c7	23	93.1	1.9	3	football	wr	n	y	l				e7	c7	l	r	l
c8	18	78.9	1.89	1	football	wr	n	y	r				e8	c9	l	r	l/r
c9	18	81.3	1.785	1	football	wr	n	y	r				e9	c5	l	r	r
c10	21	95.6	1.78	3	football	rb	n	y	r				e10	c2	l	r	r
mean	21.6	84.84	1.822	3											11	9	
sd	2.95	9.3649	0.06	1.76383													
e1	20	70.2	1.79	3	track	spr/jpr	y	y	r	r	5	y					
e2	19	88.5	1.88	2	football	rb	n	y	r	r	1	y					
e3	24	91.1	1.87	2	football	wr	n	y	r	r	10	n					
e4	25	79.3	1.8	4	fb/track	db/spr	n	y	l	l	1	y					
e5	25	106.4	1.86	4	football	lb	n	y	r	rl	10	n					
e6	23	100.8	1.82	4	fb/track	lb/spr	y	y	r	r	21	n					
e7	23	78.9	1.83	2	football	wr	n	y	l	l	36	n					
e8	20	83.4	1.83	2	track	spr/jpr	y	y	l	l	40	n					
e9	24	95.9	1.83	4	fb/track	db/spr	y	y	r	l	12	n					
e10	21	84.4	1.78	3	track	spr	y	y	r	l	21	y					
mean	22.4	87.89	1.829	3							15.7						
sd	2.22	10.975	0.033	0.94281							13.68						

Test and Leg Order Random Allocation

order	rdm #	sub	sub #	T order	rdm #	leg order	rdm #	Group
SAPD	61	14	1	DAPS	27	LR	22	I
SADP	17	4	2	SDAP	53	RL	47	I
SPAD	78	21	3	ADSP	78	RL	72	NON
SPDA	70	18	4	SADP	2	LR	65	NON
SDAP	12	2	5	PASD	27	LR	5	I
SDPA	91	23	6	PSDA	48	RL	12	I
ASPD	69	17	7	PSAD	42	RL	53	NON
ASDP	99	24	8	DASP	19	LR	32	I
APSD	62	15	9	PDSA	38	LR	57	NON
APDS	75	19	10	DSPA	25	LR	35	I
ADSP	16	3	11	DSAP	82	RL	44	I
ADPS	50	12	12	ADPS	89	RL	66	NON
PSAD	23	7	13	DPAS	67	RL	95	NON
PSDA	21	6	14	SAPD	40	LR	44	I
PASD	19	5	15	APSD	12	LR	52	NON
PADS	67	16	16	PADS	43	RL	91	NON
PDSA	27	9	17	ASPD	64	RL	70	NON
PDAS	86	22	18	SPDA	41	LR	49	I
DSAP	47	11	19	APDS	70	RL	62	NON
DSPA	43	10	20	DPSA	31	LR	86	NON
DASP	25	8	21	SPAD	93	RL	88	NON
DAPS	5	1	22	PDAS	34	LR	24	I
DPSA	76	20	23	SDPA	6	LR	38	I
DPAS	55	13	24	ASDP	51	RL	8	I

	INJURED GROUP		NONINJURED GROUP	
	TEST	LEG	TEST	LEG
1	DAPS	LR	ADSP	RL
2	SDAP	RL	SADP	LR
3	PASD	LR	PSAD	RL
4	PSDA	RL	PDSA	LR
5	DASP	LR	ADPS	RL
6	DSPA	LR	DPAS	RL
7	DSAP	RL	APSD	LR
8	SAPD	LR	PADS	RL
9	SPDA	LR	ASPD	RL
10	PDAS	LR	APDS	RL
11	SDPA	LR	DPSA	LR
12	ASDP	RL	SPAD	RL

S: SIT AND REACH TEST
A: ACTIVE KNEE EXTENSION TEST
P: PASSIVE KNEE EXTENSION TEST
D: KINCOM DYNAMOMETER TEST

Appendix F

Raw Subject Data

Legend	
Sub	Subject
sr	Sit and Reach Test score
Iake	Injured leg Active Knee Extension Test score
Uake	Un-injured leg Active Knee Extension Test score
Ipke	Injured leg Passive Knee Extension Test score
Upke	Un-injured leg Passive Knee Extension Test score
Ipt	Injured leg peak passive torque
Upt	Un-injured leg peak passive torque
Iang	Injured leg angle at peak passive torque
Uang	Un-injured leg angle at peak passive torque
Ims	Injured leg maximal stiffness
Ums	Un-injured leg maximal stiffness
Ics30	Injured leg common stiffness (30-40°)
Ucs30	Un-injured leg common stiffness (30-40°)
Ithigh	Injured leg thigh length
Uthigh	Un-injured leg thigh length
dom	Dominant leg
inj leg	Injured leg
flex	Participates in a regular flexibility program
str	Participates in a regular strength training program

group	sub	sr	lake	Uake	lpke	Upke	lpt	Upt	lang	Uang	lms	Ums	lcs30	Ucs30	lthigh	Uthigh	dom	inj leg	flex	str
con	c1	41	16	11	4	9	44.436	43.931	2	7	79.223	57.638	30.352	27.458	0.430	0.410	R	R	Y	Y
con	c2	35.5	9	10	10	10	43.795	36.573	17	12	53.667	59.867	62.388	33.223	0.420	0.420	R	L	N	Y
con	c3	37.5	4	8	4	4	31.264	23.573	3	10	46.149	32.799	30.105	20.903	0.435	0.440	L	L	N	Y
con	c4	34	15	11	8	7	40.813	41.338	8	9	56.549	57.970	40.442	26.748	0.460	0.450	R	RL	N	Y
con	c5	24	24	19	17	11	40.321	38.684	17	15	54.813	45.628	61.345	40.322	0.475	0.460	R	L	N	Y
con	c6	40	13	14	11	12	51.882	51.940	0	0	86.426	86.477	37.892	43.680	0.425	0.430	R	R	Y	Y
con	c7	14.5	16	21.5	12	19	39.554	38.436	14	17	45.531	51.049	48.802	48.894	0.460	0.470	L	L	N	Y
con	c8	23	17	15	17	16	33.963	36.864	22	18	57.770	58.205	52.561	45.038	0.440	0.450	R	R	N	Y
con	c9	38.5	8	15	10	10	40.536	38.072	9	10	53.965	43.204	47.284	34.879	0.450	0.440	R	L	N	Y
con	c10	43	11	11	9	6	45.510	42.960	0	0	70.147	64.640	33.572	30.667	0.440	0.420	R	R	N	Y
exp	e1	43.5	19	21	13	16	32.681	33.260	19	21	63.314	49.135	33.240	58.349	0.415	0.415	R	R	Y	Y
exp	e2	41	20	18	18	20	36.084	37.117	16	16	67.964	58.985	37.572	51.324	0.440	0.445	R	R	N	Y
exp	e3	18.5	21	34	16	21	41.824	37.871	18	16	65.184	45.118	57.799	46.562	0.450	0.470	R	R	N	N
exp	e4	44	15	11	10	6	33.126	38.642	7	10	47.949	61.569	31.280	41.084	0.445	0.440	L	L	N	Y
exp	e5	36	15	8	12	5	61.100	62.087	3	2	65.952	72.593	57.993	41.903	0.430	0.440	R	RL	N	Y
exp	e6	34.5	11	9	8	8	53.392	46.423	0	0	90.694	79.570	44.625	30.249	0.465	0.450	R	R	Y	Y
exp	e7	25.5	23	22.5	20.5	13.5	41.459	38.393	13	20	57.718	56.767	47.788	40.574	0.450	0.445	L	L	N	Y
exp	e8	27.5	26	17.5	21	14	52.140	58.099	8	5	69.642	72.255	56.675	59.271	0.440	0.455	L	L	Y	N
exp	e9	34	18	23	8.5	7	45.119	42.926	12	5	92.287	85.142	38.105	35.973	0.480	0.480	R	L	Y	Y
exp	e10	49	15	12	6	5	51.412	55.843	0	0	85.709	89.566	27.349	41.457	0.420	0.420	R	L	Y	Y