NEUROMECHANICAL FACTORS RESPONSIBLE FOR THE GENERATION OF MOMENTS ABOUT THE KNEE

by

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BY

SANDRA CHRISTINE WEBBER

A Thesis/Practicum submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements for the degree of

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Abstract

Purpose: The moment/angular velocity relationship derived from human strength tests does not resemble the in vitro force/velocity relationship. In particular, the maximum eccentric:isometric moment ratio does not approach that demonstrated in isolated muscle experiments. As well, the mechanisms responsible for the generation of moment during eccentric contractions is not well understood. The purpose of this study was to examine the actomyosin dependent elastic contribution to eccentric moment generation in vivo and to contrast maximal voluntarily generated eccentric moments with those produced involuntarily, that is with lengthening imposed over a short range of motion while an isometric contraction is ongoing. In addition, concentric, eccentric and isometric moment/angle/angular velocity relationships for the knee extensors and flexors were evaluated in active, non weight-trained (NWT) and weight-trained (WT) males in order to elucidate differences in neural control, mechanical factors and intrinsic muscular factors which influence strength.

Subjects: NWT males (n = 15, age = 27.5 years ± 4.5 SD, mass = 76.9 kg ± 4.9 SD) and WT males (n = 15, age = 25.1 years ± 4.9 SD, mass = 80.6 ± 16.2 SD) were recruited for the study. WT subjects participated in lower extremity resistance training 3.7 ± 1.7 SD times/week.

Methods: Maximum voluntary isometric moment (MVC) was determined at 70° (0° = full knee extension) for the knee extensors and at 25° for the knee flexors (Kin-Com 500H dynamometer). Then, while each subject performed an isometric contraction of the knee extensors at 60° of knee flexion, a 12° angular displacement was imposed at 100°/s resulting in lengthening of the activated knee extensors (imposed eccentric contraction). This procedure (step test) was performed at 10 different initial (pre-perturbation) isometric levels ranging from approximately 5 to 95 % of MVC and the magnitudes of the resulting imposed eccentric moments were measured. Maximal effort knee extensor and knee flexor

isovelocity strength tests were then performed (5 to 95°, 3 repetitions, ± 50, 100, 150, 200, 250°/s).

Analyses: The relationship between the pre-perturbation isometric moment and the step test peak imposed eccentric moment was determined for each subject and for the entire group (n=30) with linear regression analysis. The predicted maximum imposed eccentric moment was compared with the maximum voluntary eccentric moment (same joint angle and same velocity) to quantify the degree of neural regulation during voluntary eccentric contractions. Peak moment (average peak moment of 3 repetitions), absolute peak moment (moment with the greatest magnitude recorded during the 3 repetitions), and angle-specific moment (at 70° for knee extensor tests and at 25° for knee flexor tests) were determined for each strength test velocity and normalized to body mass. ISOMAP software (Isodyne Inc., Winnipeg, MB) was used to generate two-dimensional strength maps (50 X 50 matrix) for the knee extensors and knee flexors for both groups to display and compare maximum moment generating capabilities over the entire tested range of motion within the ±250°/s velocity spectrum.

Results and Conclusions: A strong linear relationship was observed between the peak imposed eccentric moment and the pre-perturbation isometric moment ($n = 30$, $y = 1.44x + 6.26$, $r = 0.99$). This finding is consistent with results of previous in vitro analyses and suggests that actomyosin dependent elasticity is largely responsible for the increased force/moment produced during eccentric contractions. The maximum predicted imposed eccentric moment was 150% MVC which is consistent with in vitro force/velocity data. The maximum predicted imposed eccentric moment was 204% of the mean angle and velocity matched eccentric moment generated with maximal effort. This substantial difference may be explained by the existence of a potent neural regulatory mechanism which limits eccentric moment generation during voluntarily controlled movements.

WT subjects generated greater knee extensor and flexor MVC moments compared to the NWT subjects ($p<0.05$). Analysis of moment/angular velocity data demonstrated that the strength of the knee extensors and flexors was greater in the WT group as compared to the

NWT group when tested isometrically and eccentrically. The WT subjects also produced greater concentric knee extensor moments, however no group differences were noted in the concentric knee flexor results. Strength map analysis provided for a more comprehensive analysis of strength differences that exist between these two groups. Difference maps revealed that the WT subjects were stronger than the NWT subjects over 14.7% of the knee extensor strength map surface and over 25.2% of the knee flexor map surface ($p<0.05$). These strength differences spanned different ranges of motion for the knee extensors (49-95°) and flexors (5-75°), but were primarily located in the eccentric and isometric portions of the maps.

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Definition of Terms

Muscle contraction - neural activation of muscle resulting in actomyosin cross-bridge cycling.

Concentric contraction - shortening of the overall muscle length during neural activation.

Eccentric contraction - lengthening of the overall muscle length during neural activation.

Isometric contraction - the overall muscle length remains constant during neural activation.

Force - is proportional to the product of mass (kg) and acceleration (m/s^2). Force is a linear term expressed in Newtons where 1 N = 1 kgm/s^2.

Moment arm - the perpendicular distance from the line of action of a force to the axis of rotation.

Moment - the product of a force and the corresponding moment arm. Moment is an angular term which depicts the tendency of a force to produce rotation about a specified axis. Moment is expressed in Newton-metres (Nm).

Resultant joint moment - represents the sum total of all muscular, tendinous, ligamentous, cartilaginous, capsular, and bone-on-bone forces acting about the instantaneous axis of rotation of the joint.

Angular velocity - the rate of change of angular displacement expressed in radians or degrees per second (°/s).

Angular acceleration - the rate of change of angular velocity expressed in radians or degrees per second squared ($°/s^2$).

Knee joint angle - the angle defined by the greater trochanter and the lateral malleolus with the lateral femoral condyle as the vertex where 0° = full knee extension. Flexion of the knee corresponds to a positive joint angle (e.g. 90° knee joint angle).

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Introduction

The ability to accurately evaluate neuromuscular performance is of primary importance in the fields of rehabilitative medicine, athletic training, and ergonomics. Measures of strength, speed, power, endurance, agility, and flexibility are frequently used to depict neuromuscular performance. The most commonly measured component of neuromuscular performance is strength. Strength can be operationally defined as "the ability of the neuromuscular system to control rotation of the body segments". The recent trend towards evidence-based practice and the use of validated outcome measures has placed increased emphasis on the objective quantification of strength in rehabilitation.

The generation of purposeful human motion requires the complex coordination of neuromuscular activity to control movement of body segments about multiple joints through substantial ranges of motion at different velocities. The establishment of objective strength values in normal populations is important to provide guidelines for rehabilitation of patients with pathology (Dibrezzo et al. 1985, Goslin and Charteris 1979, Highgenboten et al. 1988, Kannus 1988, Kannus et al. 1987, Nosse 1982). Dynamometers have greatly expanded our capabilities of studying dynamic and static muscle function in comparison to previously available strength assessment techniques. Dynamometers have the ability to provide objective, reliable measurement of eccentric, concentric and isometric strength about different joints over multiple angular velocities and over a significant portion of the range of motion (Gleeson and Mercer 1992, Greenfield et al. 1990, Hageman et al. 1989, Harding et al. 1988, Hortobagyi and Katch 1990, Kues et al. 1992, Montgomery et al. 1989, Wessel et al. 1992). However, despite the fact that dynamometers and their software packages are capable of quantifying strength in a comprehensive manner, strength assessments have frequently only evaluated moments generated during concentric contractions at two or three speeds and analysis of the data has largely been focused on measuring the peak moment (or peak torque) recorded at one joint angle (Goslin and Charteris 1979, Holmes and Alderink 1984, Kannus and Beynnon 1993, Lord et al. 1992, Murray et al. 1984). Because adaptations in strength have been shown to be contraction type, velocity, range of motion and skill specific (Morrissey et al. 1995), a more comprehensive method of quantifying and depicting strength parameters is required in order to analyze strength over a greater portion of the neuromuscular system's operational domain.

The neuromuscular system exerts its influence by producing moments to control rotation of body segments over certain ranges of motion and at specific velocities of movement. Two-dimensional moment/angle and moment/angular velocity relationships have been used extensively to report strength about the knee. In this study, a new, more comprehensive method of qualitatively and quantitatively portraying strength shall be introduced and used to determine and illustrate strength differences about the knee in weight-trained (WT) and non weight-trained (NWT) males. Strength maps shall be used to depict resultant knee joint moment (RJM_k) data in relief map format throughout a sampled strength domain (throughout a specified range of motion, during different types of contractions and at different speeds of motion).

In addition, the relationship between isometric, concentric and eccentric moment generating capabilities shall be examined in this study. Despite the fact that dynamometers have been capable of measuring strength during all types of contractions, concentric and isometric strength studies have greatly outnumbered reports which have included eccentric contractions. Associated with this paucity of research on eccentric contraction is a relatively poor understanding of the mechanisms responsible for the generation of eccentric moments.

Although studies of eccentric contraction are lacking in humans, numerous in vitro investigations have been undertaken. Experiments on maximally activated isolated muscle have demonstrated that forces generated during muscle lengthening (eccentric contractions) exceed isometric forces which, in turn, exceed forces generated during muscle shortening (concentric contractions) (Edman 1988, Edman et al. 1978, Flitney and Hirst 1978, Haugen 1991, Hill 1938, Lombardi and Piazzesi 1990). Eccentric forces have been shown to reach 1.5 to 1.9 times isometric force under maximal stimulation (Edman et al. 1978, Harry et al. 1990, Haugen 1991, Lombardi and Piazzesi 1990). However, maximal effort human moment/angular velocity relationships do not resemble the maximally activated force/velocity relationships of isolated muscle experiments (Caldwell et al. 1993, Colliander and Tesch 1989, Hortobagyi and Katch 1990, Perrine and Edgerton 1978, Prietto and

Caiozzo 1989, Rodgers and Berger 1974, Westing and Seger 1989, Westing et al. 1988 and 1991, Wickiewicz et al. 1984). The discrepancies are particularly obvious when comparing the eccentric sides of the moment/angular velocity and force/velocity relationships. Human studies have demonstrated that maximal effort eccentric moments do not exceed maximum isometric moments (Dudley et al. 1990, Lacerte et al. 1992, Mayer et al. 1994, Westing and Seger 1989, Westing et al. 1988, Westing et al. 1990). Investigations involving isolated muscle preparations have demonstrated that force initially increases with increasing linear velocity of lengthening until a plateau is reached (Flitney and Hirst 1978, Harry et al. 1990, Joyce et al. 1969, Katz 1939), whereas eccentric moments generated by the knee flexors and knee extensors have generally been reported to remain the same with increasing angular velocity (Dudley et al. 1990, Griffin et al. 1993, Hageman et al. 1988, Westing and Seger 1989, Westing et al. 1988 and 1991).

The differences between maximal effort moment/angular velocity relationships and maximally activated force/velocity relationships need to identified and studied. Generation of moments in vivo involves the complex interaction of muscular, mechanical and neural factors, most of which do not exert a significant influence in isolated muscle experiments. Therefore it is not surprising that the relationships should take on different shapes and relative magnitudes. However, one would expect that by controlling for some of the different factors which influence moment generation in vivo, similarities between in vivo moment/angular velocity and in vitro force/velocity relationships would emerge. Analysis of moment/angular velocity relationships generated with neural influences minimized may provide valuable information regarding the most influential factors responsible for the differences observed between in vivo and in vitro relationships. For example, investigators have hypothesized that the eccentric side of the in vivo moment/angular velocity relationship does not resemble that demonstrated in vitro largely because of the existence of a neural regulatory mechanism which limits moment generation during high level eccentric contractions (Caiozzo et al. 1981, Gulch 1994, Perrine and Edgerton 1978, Stauber 1989, Westing and Seger 1989, Westing et al. 1988). As yet, the ability to quantify the upper limit of the eccentric moment generating ability in humans for comparison to maximal effort eccentric moments has been lacking.

The relationships among maximal isometric moments, maximal voluntary eccentric moments and imposed eccentric moments will also be investigated in this study. Peak knee extensor moments generated under maximal effort shall be compared with moments produced during imposed eccentric contractions at the same velocity of movement and at the same joint angle to identify and quantify the degree of neural regulation accompanying voluntary eccentric activity. Using this technique, neural regulation levels will be compared between WT and NWT males. This information will contribute to our understanding of neural control during eccentric moment generation and may be used to influence athletic and rehabilitative training programs designed to improve eccentric strength. Further understanding of the mechanisms responsible for eccentric moment generation will add to our knowledge of the differences that exist among eccentric, concentric and isometric contractions.

Review of Literature

Concentric Force/Velocity and Moment/Angular Velocity Relationships

Concentric force/velocity relationships determined for isolated muscle have been shown to differ in shape from concentric moment/angular velocity relationships generated in vivo (Perrine and Edgerton 1978, Wickiewicz et al. 1984). As well, moment/angular velocity plots have been shown to take on different shapes depending on the movements and muscle groups tested. (Caldwell et al. 1993, Colliander and Tesch 1989, Richards 1981, Wickiewicz et al. 1984).

The classic study of Hill (1938) demonstrated that the relationship between muscle force and shortening velocity can be represented by the single rectangular hyperbola in isolated muscle specimens under controlled maximal stimulation. Hill's experiments on whole sartorius muscles from the frog revealed that force increased as the velocity of muscle shortening decreased until a maximum force was attained at zero velocity. Investigators have shown that the force/velocity relationship for isolated single muscle fibres takes on a more complex shape than that observed in whole muscle (Edman et al. 1978, Edman 1988). Edman (1988) demonstrated that a double-hyperbolic force/velocity relationship existed for isolated frog muscle fibres. This force/velocity relationship followed Hill's hyperbolic equation (Hill 1938) up to about 78% of maximal isometric force where it then deviated from the curve and assumed a second hyperbolic path.

Although moment/angular velocity relationships derived from isovelocity human strength studies have demonstrated that concentric moments decrease with increasing angular velocity and that moments generated isometrically exceed moments generated concentrically, the shape of the moment/angular velocity curve does not closely resemble the hyperbolic force/velocity curve of isolated muscle preparations (Perrine and Edgerton 1978, Wickiewicz et al. 1984). This is likely related to the fact that multiple neural, mechanical and intrinsic muscular factors influence moment generation in vivo. It has been proposed that the in vivo moment/angular velocity curve for concentric muscle activity may best be described by a linear or cubic model but mathematical description of the curve has not been pursued (Taylor et al. 1991). Baltzopoulos and Brodie (1989) and Osternig (1986) in their reviews of isovelocity dynamometry reported that concentric knee extensor moment values generally decrease with increasing angular velocity. However, they also noted that several researchers have observed a plateauing of moment values at lower velocities (50 - 192°/s) (Perrine and Edgerton 1978, Prietto and Caiozzo 1989, Wickiewicz et al. 1983). Perrine and Edgerton (1978) suggested that this plateauing of concentric knee extensor moments at lower velocities may be attributed to neural inhibition which limits development of muscle tension at these velocities. The generation of moment about a joint involves the activation of agonistic and antagonistic muscle groups, each potentially having its own level of neural activation. The force contribution of each muscle is dictated by its individual moment arm length which varies with joint angle (Hoy et al. 1990), force/velocity relationship, activation level and muscle fibre make-up. Therefore, it is understandable that the in vivo moment/angular velocity relationship differs from the in vitro force/velocity relationship for the above listed reasons, and because different neural recruitment patterns exist for both the agonist and antagonist (Bobbert and Harlaar 1992, Caldwell et al. 1993).

Studies by various investigators have supported the finding that maximum isometric moments generated by the knee extensors exceed concentric knee extensor moments which decrease with increasing velocity of shortening (Alexander 1990, Caldwell et al. 1993, Perrine and Edgerton 1978, Prietto and Caiozzo 1989, Taylor et al. 1991, Thorstennson et al. 1976, Westing et al. 1988). Similar concentric moment/angular velocity relationships have been demonstrated for the knee flexors (Caldwell et al. 1993, Colliander and Tesch 1989, Prietto and Caiozzo 1989), elbow flexors (Griffin 1987, Griffin et al. 1993, Hortobagyi and Katch 1990, Komi 1973), elbow extensors (Hortobagyi and Katch 1990), shoulder internal and external rotators (Mont et al. 1994) and ankle plantarflexors (Washburn et al. 1992). Although the moment/angular velocity relationships demonstrated in these studies showed a similar pattern for movements about different joints (i.e. decreasing concentric moments with increasing velocities of testing), the slopes of the moment/angular velocity relationships were different. For example, the moment/angular velocity relationship for the knee flexors has been shown to demonstrate a less dramatic decrease in moment output with increasing velocity compared to the knee extensors (Caldwell et al. 1993, Colliander and Tesch 1989, Richards 1981, Wickiewicz et al. 1984).

Eccentric Force/Velocity and Moment/Angular Velocity Relationships

In comparison to concentric differences, even greater discrepancies have been identified on the eccentric side of force/velocity and moment/angular velocity relationships. Not only are the shapes of eccentric force/velocity and moment/angular velocity relationships different, but the relative eccentric:isometric magnitudes of forces and moments have also been shown to be quite different.

The in vitro force/velocity relationship for lengthening of frog, mouse and cat skeletal muscle reveals that eccentric force output increases with increasing velocity of stretch up to approximately 1.5 times maximal isometric force followed by a plateau region where force remains relatively constant with any additional increases in velocity of lengthening (Flitney and Hirst 1978, Harry et al. 1990, Joyce et al. 1969, Katz 1939). Edman et al. (1978) and Haugen (1991) found that imposing a stretch on single frog muscle fibres resulted in increases in force to approximately 1.7-1.9 times tetanized isometric levels.

Marked differences have been identified between human eccentric moment/angular velocity relationships and isolated muscle force/velocity relationships. Human strength assessments have generally found that maximum eccentric moments do not exceed maximum isometric moments and do not increase in magnitude with increasing velocity of lengthening (Dudley et al. 1990, Lacerte et al. 1992, Mayer et al. 1994, Westing and Seger 1989, Westing et al. 1988, Westing et al. 1990). Westing and colleagues (1988) studied knee extensor eccentric moment generation in a group of 21 young active males. Westing and co-workers found that eccentric knee extensor peak moments and angle-specific moments (measured at 30°, 40°, 50°, 60° and 70°) recorded over the speeds of 0, 30, 120, and 270°/s did not change with increasing velocity of testing. The eccentric peak moments and the eccentric angle-specific moments were significantly greater than the corresponding concentric moments recorded in this study. However, the eccentric peak moments were not statistically greater than maximum isometric moment. One year later, Westing and Seger reported eccentric and concentric peak moments for knee flexion and knee extension in 20 young women at 5 speeds ranging from 60-360°/s. Once again they found that peak eccentric moments did not change with increasing velocity of eccentric tests and that these values were not significantly greater than maximum isometric moment. Peak concentric moments for the flexors and extensors decreased with increasing velocity of shortening. Concentric peak moments were significantly lower than eccentric peak moments and values for the quadriceps were always greater than corresponding hamstring moment values.

Hageman et al. (1988) and Griffin et al. (1993) also measured knee flexor and extensor peak eccentric moments over different speeds (30 and 180°/s, 30 and 120°/s respectively), demonstrating that eccentric moments do not increase in magnitude with increasing velocity of testing. No isometric strength evaluations were included in these studies. Dudley and colleagues (1990) found that angle-specific eccentric knee extensor moments recorded at 45° of knee flexion did not significantly increase above isometric levels when tested over nine angular velocities ranging from 10-210°/s. Westing and co-workers (1990) found no significant differences between maximum eccentric moments and maximum isometric moment when knee extensor eccentric moments were measured at speeds of 60, 180, and 360°/s.

It has been suggested that eccentric moment/angular velocity relationships may vary depending on the muscle groups and specific movements tested (Griffin et al. 1993 Westing and Seger 1989, Westing et al. 1988), however this hypothesis has not been substantiated in the literature. Besides being extensively studied for the knee extensors, eccentric moment/angular velocity relationships have also frequently been reported for the elbow flexors. Similar to the knee extensors, both elbow flexor and elbow extensor eccentric moments have been shown to be consistently greater than concentric moments at matched velocities (Griffin 1987, Griffin et al. 1993, Hortobagyi and Katch 1990, Komi 1973, Rodgers and Berger 1974). However, some studies have reported moment/angular velocity (M/ω) relationships which have departed from that observed for the knee extensors. A few studies have reported that elbow flexor moment production initially increases and then decreases with increasing velocity of lengthening (Griffin 1987, Rodgers and Berger 1974). Unfortunately, Griffin (1987) noted that the intraclass correlation coefficients used to determine test-retest reliability of the protocol used in this study were unacceptably low. As well, the study by Rodgers and Berger (1974) involved only a very small range of relatively slow test velocities (18, 45, and 72°/s). In a later study, Griffin et al. (1993) reported that moment values remained unchanged with increasing velocity from 30 to 120°/s during eccentric tests of the elbow flexors. Isovelocity strength evaluations for shoulder movements have also generally demonstrated that peak eccentric moments do not change with velocity of testing (De Pauw 1996, Mayer et al. 1994).

Hortobagyi and Katch (1990) proposed that eccentric and concentric moment/angular velocity relationship shapes may vary depending upon individual levels of strength. Hortobagyi and Katch performed isovelocity tests of the elbow flexors and extensors on 40 healthy young men. Each subject performed two maximal eccentric and concentric contractions at each test speed (30, 90 and 120 °/s) for the elbow flexors and extensors. Subjects were classified as being either high strength or low strength based on their cumulative peak moment scores recorded during the concentric and eccentric tests. The high strength group (n = 20) had significantly greater body mass (and significantly greater estimated lean body mass) and produced absolute moments which were on average approximately 25% greater than moments generated by the low strength group. The high strength group consisted of WT subjects (college athletes and recreational weight-lifters). Six of the 20 subjects in the low strength group were runners while the others pursued non-specified recreational activities. Of note, despite the fact that subjects in the high strength group had significantly greater body masses than subjects in the low strength group (mean mass of high strength = 90.9 kg whereas mean mass of low strength = 76.7 kg), strength measurements were not normalized to body mass. It is possible that normalization of moment values to body mass may have altered the findings reported in this study. However, using absolute values, the authors demonstrated that the shape of the moment/angular velocity relationship differed between the groups. Although eccentric moments exceeded concentric moments for both groups, for the low strength group, concentric moments did not demonstrate a linear drop-off with increasing velocity of testing (moments remained constant with increasing concentric velocity). As well, for the low strength group, the eccentric moments remained constant despite changes in the velocity of testing. However, moment output decreased with increasing concentric velocity and increased with increasing eccentric velocity for the high strength group. Hortobagyi and Katch postulated that these differences observed in the shapes of the moment/angular velocity relationships might be explained by differences in relative levels of neural inhibition, muscle size, muscle fibre types, muscle architectural properties and muscle extensibility in subjects of different training backgrounds.

The majority of human strength evaluations have demonstrated that concentric moments decrease with increasing velocity of testing (Alexander 1990, Caldwell et al. 1993, Edman et al. 1978, Edman 1988, Hill 1938, Perrine and Edgerton 1978, Prietto and Caiozzo 1989, Taylor et al. 1991, Thorstennson et al. 1976, Westing et al. 1988). However, the slope of this decline in the moment/angular velocity relationship does not follow the hyperbolic path demonstrated in the in vitro force/velocity relationship likely due to a combination of neuromechanical factors that differentiate the isolated muscle preparation from the in vivo circumstance. Comparisons between the eccentric force/velocity relationship and the eccentric moment/angular velocity relationship have demonstrated even greater differences in the shapes. Unlike investigations on isolated muscle which have shown that eccentric forces may reach 1.5-1.9 times maximal isometric force (Edman et al. 1978, Flitney and Hirst 1978, Harry et al. 1990, Haugen et al. 1991, Joyce et al. 1969, Katz 1939), constant angular velocity in vivo studies have generally determined that peak eccentric moments do not exceed maximum isometric values (Dudley et al. 1990, Lacerte et al. 1992, Mayer et al. 1994, Westing and Seger 1989, Westing et al. 1988, Westing et al. 1990). However, if only musculoskeletal factors were considered, it would seem plausible that the eccentric:isometric ratio seen in vivo should resemble the ratio demonstrated in vitro where eccentric moments reach 1.5 - 1.9 times maximum isometric force. As well, the force/velocity relationship demonstrates that eccentric forces initially increase with increasing velocity of lengthening, whereas most human strength studies have found no increase in peak eccentric moments with increasing velocity of testing (De Pauw 1996, Dudley et al. 1990, Griffin et al. 1993, Hageman et al. 1988, Mayer et al. 1994, Westing and Seger 1989, Westing et al. 1988 and 1991).

Eccentric Force/Moment Generation

Investigators have attempted to determine the mechanisms responsible for the enhanced force produced during eccentric contractions (1.5-1.9 times maximum isometric force and greater than 2 times concentric forces in vitro). Some studies have also attempted to determine why eccentric values achieved during human strength tests do not exceed isometric levels as occurs in isolated muscle investigations. The sliding filament theory involving cross-bridge cycling between thick and thin filaments of muscle has been widely accepted to explain the generation of force in striated muscle. However, the specific model that best describes muscle characteristics during both shortening and lengthening at different velocities has encountered some debate (Harry et al. 1990, Huxley 1957, Huxley and Simmons 1971). Different theories have been proposed to explain the mechanism(s) responsible for the increased force production in eccentric contractions. Some researchers have suggested that eccentric contractions are associated with greater force production because the force required to break actomyosin cross-bridges (in lengthening contractions) is greater than that required to maintain cross-bridge engagement in isometric contractions (Enoka 1988a, Gulch et al. 1991, Stauber 1989). Other investigators have proposed that eccentric contractions may be associated with increased release of calcium into the sarcoplasm causing greater activation of muscle (Haugen 1991). Results of studies on isolated muscle have indicated that muscle tissue exhibits elastic behaviour. Researchers currently believe that this elastic component in muscle may be largely responsible for the greater force produced during eccentric contractions (Blange et al. 1972, Flitney and Hirst 1978, Huxley and Simmons 1971, Morgan 1977, Suzuki and Sugi 1983).

Although researchers have proposed that greater forces may be required to allow for detachment and cycling of actomyosin cross-bridges during eccentric contractions (Enoka 1988a, Gulch et al. 1991, Stauber 1989), this theory has not been supported by any scientific work. If forceful separation of actomyosin cross-bridges did occur during lengthening contractions, this might result in the production of movement which would lack smoothness (Enoka 1988a, Stauber 1989). As well, the mechanism responsible for detachment of cross-bridges may be different during eccentric and concentric contractions (Enoka 1988a). The fact that ultrastructural muscle damage associated with eccentric muscle activity has largely been localized to the Z-discs and the cytoskeleton rather than the filaments and cross-bridges themselves suggests that forceful dissociation of the cross-bridges does not likely occur during normal lengthening (Armstrong 1990, Friden et al. 1983, Friden and Lieber 1992, Lieber et al. 1991, Newham et al. 1983, Waterman-Storer 1991).

Haugen (1991) proposed that the increased force produced during eccentric contractions was the result of an increased release of calcium into the sarcoplasm causing greater activation of muscle. He studied calcium concentrations in frog muscle fibres immediately before and after a quick stretch was applied. Haugen found that the quick stretch caused a significant increase in force (approximately 2 times isometric values) but the calcium transients were basically unaffected by the stretch. Based on these results, Haugen proposed that the mechanism responsible for the enhanced force produced in eccentric contractions must lie beyond the calcium release step in excitation-contraction coupling. He felt it conceivable that stretch might affect the calcium sensitivity of the calcium-dependent contractile regulation system but stated that it was doubtful that this mechanism could be responsible for the entire increase in force demonstrated during quick stretch experiments. He suggested that the phenomenon might be related to the interaction between the myosin head and the actin filament during lengthening.

Studies on isolated muscle have confirmed that muscle tissue exhibits elastic behaviour which is believed to be largely responsible for the greater force produced during eccentric contractions (Blange et al. 1972, Flitney and Hirst 1978, Huxley and Simmons 1971, Morgan 1977, Suzuki and Sugi 1983). Materials or tissues are said to exhibit elastic behaviour when external energy that is entered into the system by applying a stretch is utilized after deformation to return the material to the original dimension. In the case of lengthening deformation of muscle tissue, elastic components provide a resistance to the applied stretch. Tissues which are purely elastic are capable of withstanding reasonable magnitudes of stretch without permanent deformation. Soft tissues such as muscle, tendon and ligament exhibit elastic properties mixed with other mechanical and physiological characteristics.

A three-component model consisting of a contractile component, a parallel elastic component and a series elastic component has been used to explain some of the mechanical characteristics of muscle behaviour (Enoka 1988a, Gulch et al. 1991, Taylor et al. 1991). Actin and myosin filaments and their cross-bridges are represented by the contractile component. The parallel elastic component represents connective tissues such as the sarcolemma, endomysium, perimysium and epimysium which are parallel to the contractile elements and exert a passive force when muscle tissue is stretched beyond its resting length. The relative contribution of the passive elastic elements to total muscle force increases with increases in muscle length. The series elastic component represents elastic elements within the sarcomeres and the tendon which are in series with the contractile components. Z bands, titin, nebulin, actin and myosin filaments and their crossbridges may all contribute to series elasticity (Blange et al. 1972, Horowits 1992, Huxley and Simmons 1971, Labeit and Kolmerer 1995, Suzuki and Sugi 1983, Trombitas and Pollack 1993, Wakabayashi et al. 1994). Series elastic elements are put under tension by the force developed by the crossbridges of the muscle and by stretching of the muscle. The series elastic component of muscle has been divided into "active" and "passive" components. The passive component refers to tendinous and muscular connective tissue whose contributions to total muscle force are only significant at longer muscle lengths. In isolated muscle, the elastic properties of the "active" components have been shown to be dependent on the relative tension in the muscle (Blange et al. 1972, Flitney and Hirst 1978, Wise et al. 1973) which is dependent on the number of actomyosin cross-bridges engaged at a particular time, suggesting that the elasticity may lie within the molecules which form the crossbridges (Blange et al. 1972, Flitney and Hirst 1978, Gulch et al. 1991, Hill 1968, Huxley and Simmons 1971, Rack and Westbury 1974, Wise et al. 1973). The active series elastic components have been shown to require only a very small change in length (up to about 0.2% of the muscle length) to reach their elastic limit (Enoka 1988a, Hill 1968, Rack and Westbury 1974).

Evidence for the existence of an active series elastic component has largely been gained from results of quick-release studies on isolated muscle (Blange et al. 1972, Bressler and Clinch 1974, Huxley and Simmons 1971, Lensel-Corbeil and Goubel 1990, Wise et al. 1973). During quick-release experiments, muscle is activated at a fixed length (isometric condition) and then the muscle is suddenly allowed to shorten (concentric condition). Force is monitored during these experiments. Muscle has been shown to exhibit a biphasic shortening response when it is released from isometric contraction and is allowed to shorten against a load that is less than maximum isometric tension (Cavagna 1977, Close 1972, Rack and Westbury 1974). The initial shortening response is rapidly completed within a few milliseconds. This characteristic of muscle shortening has been attributed to the rapid release of energy stored in the series elastic components. The second slow phase of shortening has been attributed to actions of the contractile component of muscle. Blange et al. (1972) applied sudden shortening to one end of isolated rat soleus muscle while the muscle was activated by stimulation at different frequencies. The resulting drop in tension was recorded and force-shortening curves were constructed. Stiffness-force curves derived from data taken at different stimulation frequencies differed in a consistent manner indicating that muscle stiffness (change in force/change in length) is related to the degree of activation of the contractile component which suggests that series elasticity is dependent on actomyosin cross-bridge engagement. Bressler and Clinch (1974) studied quick-release in toad sartorius muscle to determine the relationship between muscle stiffness at any given muscle length and maximum isometric tension at that length. A record of release of non-stimulated muscle was subtracted from the record of release of stimulated muscle at the identical length to correct for the contribution of the parallel elastic component. A strong positive correlation was found between maximal isometric tension level (which was varied by changing the length of the muscle) and muscle stiffness suggesting that "the force generating elements within the muscle may be sites of relatively high compliance."

Huxley and Simmons (1971) also used a quick-release technique on isolated fibres of frog sartorius muscle to investigate series elastic properties of muscle. They discovered that the change in elastic response to change in fibre length was proportional to alterations in tension and therefore concluded that series elasticity varied in direct proportion to the number of activated cross-bridges.

Sudden stretches applied to single muscle fibres or whole muscles during maximal isometric stimulation have also been used to study elastic properties of muscle (Edman et al. 1978, Ford et al. 1981, Flitney and Hirst 1978, Gulch et al. 1991, Haugen 1991, Joyce et al. 1969, Morgan 1977). Ford and coworkers (1981) studied tension changes in stimulated isolated fibres of frog tibialis anterior muscles when sudden length changes were imposed. The tension was shown to change simultaneous with the step change in length. Peak tension changes decreased in magnitude as the amount of filament overlap decreased at longer muscle lengths suggesting that series elasticity is related to the number of activated cross-bridges. Flitney and Hirst (1978) also determined that the stiffness of sarcomeres (measured by tension responses to length changes in frog muscle) decreased at greater sarcomere lengths. Values for the stiffness of sarcomeres and for the initial force increment with stretch were both shown to fall to zero at extrapolated sarcomere lengths where actin and myosin were no longer overlapping. This is consistent with the notion that active series elasticity is dependent on cross-bridge formation. Edman and colleagues also determined that increased force was produced when isolated frog muscle fibres were stretched during isometric contraction. Increased velocity of stretch (from 0.1 to 0.3 fibre lengths/s) was associated with an increase in the magnitude of the force recorded during the stretch. This finding is in agreement with the results of other in vitro investigations which demonstrated that eccentric forces increased with increased velocity of lengthening (Flitney and Hirst 1978, Harry et al. 1990). The fact that the relative elastic contribution to eccentric force generation is velocity dependent is consistent with the notion that the components responsible for elastic properties also exhibit viscous properties (Gulch et al. 1991).

Some researchers have attempted to investigate muscle series elasticity and its relationship to the generation of moments during eccentric muscle activity in humans

(Cnockaert et al. 1978, Gulch et al. 1991, Pousson et al. 1990, Thomson and Chapman 1988). However, additional considerations must be factored in when examining the in vivo system such as the different muscle temperatures, the different amounts of connective tissue involved and the influence of the nervous system on musculoskeletal components. Gulch and co-workers (1991) studied isometric and forced-eccentric moment generation in top-performance kayak racers (n=16, 17-22 years of age) and untrained female students (n=15, 17-18 years of age). To simulate the quick-stretch experiments performed in vitro, quick stretches were applied in vivo during maximal voluntary isometric contractions of the elbow flexors. Subjects were asked to perform maximal effort isometric contractions (MVC) of the elbow flexors at 90° elbow flexion. Then, 1.5 seconds after onset of the isometric contraction, motion was imposed at a constant speed in the extension direction causing forced-lengthening of the flexor muscles during activation (defined as a forced-eccentric contraction). Forced-eccentric contractions were imposed at different joint angles, velocities and angular displacements, however, the range of joint angles, velocities and angular displacements studied were not specified. The investigators did specify that the maximal angular velocity of testing was quite low at 70°/s. Upon completion of the lengthening contraction subjects were asked to perform an isometric contraction at the new joint angle for another two seconds. Results showed that a constant external force plateau was quickly reached during the pre-stretch isometric contraction. Forced lengthening induced a double-peaked increment in force with the maximal value occurring at the end of the eccentric phase. Unfortunately these double-peaked increments in force were not quantified and the mechanism responsible for the generation of this force was not discussed. The external force increments occurred in the absence of corresponding changes in EMG during isovelocity imposed eccentric conditions. From the published figures, it appears that the peak imposed eccentric force values were larger than the pre-stretch isometric force levels by approximately 15-20%. External force decayed exponentially after the forced-eccentric contraction to a new isometric level (at the new joint angle) which was higher than the pre-stretch isometric force level. These isometric and forced-eccentric tests were performed on all subjects prior to and on completion of a combined concentric and eccentric strength training program. Strength training resulted in parallel increases in isometric and forced-eccentric forces in both groups. Because forced-eccentric contractions resulted in increased force production similar to quick-stretch studies in vitro, Gulch and colleagues concluded that elementary properties of the muscle fibres themselves must be responsible for the enhanced force demonstrated during eccentric contractions. They attributed this behaviour to the viscoelastic properties of muscle which seemed to be dependent on the number of activated cross-bridges. Interestingly, the authors noted that isometric force levels were lower when immediately followed by a forced-lengthening contraction. The investigators postulated that the lower pre-stretch isometric measurements may have been the result of reduced motivation on the part of subjects anticipating the oncoming stretch.

Thomson and Chapman (1988) also used imposed eccentric contractions to examine the effects of change in muscle length, rate of stretch and amplitude of stretch on eccentric moment generation in humans. Imposed eccentric moments were compared with isometric moments for forearm supination in five men. Maximal voluntary isometric contractions were interrupted by imposed stretches at different constant velocities (60, 144 or 227 °/s) and of different amplitudes (80 or 160°) over different parts of the available range of motion (170-90°, 90-10° or 170-10°). Excess moment was calculated as the ratio of the eccentric moment recorded immediately before the dynamometer reached its stop angle over the maximal isometric moment predetermined for that joint angle (dynamometer stop angle). This differed from the calculation used by Gulch and co-workers (1991) who calculated the increase in moment relative to maximal isometric moment achieved at the pre-stretch joint angle. The method used by Gulch and colleagues likely overestimated the true eccentric:isometric moment ratio for a particular joint angle, whereas the method used by Thomson and Chapman likely provided a more representative value. Thomson and Chapman found that excess moment decreased significantly with increasing stretch amplitude. The authors postulated that the stretches which involved greater angular displacements may have stretched muscles outside the limit of short-range-stiffness (Rack and Westbury 1974). Similar to the in vitro force/velocity relationship, excess moment increased significantly from slow to medium stretch velocities and plateaued over the medium and fast velocities. Peak imposed eccentric moments ranged from approximately 1.08-1.26 times maximum isometric measurements. Thomson and Chapman noted that the magnitude of the change in moment from isometric to eccentric levels was small compared to results of in vitro experiments. They suggested this might be due to the fact that greater amounts of passive series elasticity are included in in vivo strength tests (e.g. in the biceps tendon) or that the increased temperature of human muscle might reduce muscle stiffness leading to a smaller increase in moment during stretch. EMG analysis was included in this study to determine whether reflex recruitment of additional motor units or increased discharge of active motor units influenced the stretch response. No significant differences in mean levels of quantified EMG were seen at the end of stretch compared to isometric contractions at the same forearm position. Because EMG changes were seen during the stretch in only two of the five subjects, the researchers concluded that intrinsic mechanical properties within the muscles were primarily responsible for the enhanced generation of moment in eccentric contractions.

The stretch-shortening phenomenon observed in humans also supports the existence of a series elastic component within muscle (Cavagna et al. 1968, Cavagna 1977). Increased work and/or power has been demonstrated during a concentric contraction which is immediately preceded by an "active stretch" (i.e. an eccentric contraction) of the involved muscle groups. Lengthening of activated muscles allows for storage of mechanical energy in the series elastic components which is then released during the shortening phase (concentric contraction). Stretching of muscles during eccentric contraction may also activate muscle spindles resulting in the associated reflex excitation of motoneurons. Therefore, the enhanced generation of moment demonstrated in the concentric contraction which is immediately preceded by an eccentric contraction has been attributed to the combined effects of series elasticity and stretch reflex activation potentiation (Komi 1984). The ability to use stored elastic energy to enhance concentric activity has been shown to be dependent on the time delay between contractions, the magnitude of the stretch and the velocity of the stretch (Cavagna 1977, Edman et al. 1978, Rack and Westbury 1974).

Summary of In Vitro and In Vivo Eccentric Studies

Studies on isolated muscle have demonstrated that eccentric forces reach 1.5 to 1.9 times maximal isometric force (Edman et al. 1978, Flitney and Hirst 1978, Harry et al. 1990, Joyce et al. 1969, Katz 1939). The fact that eccentric forces exceed isometric and concentric forces has largely been attributed to the existence of series elasticity related to cross-bridge engagement (Blange et al. 1972, Hill 1968, Gulch et al. 1991, Huxley and Simmons 1971, Flitney and Hirst 1978, Rack and Westbury 1974, Wise et al. 1973). Similar characteristics have been shown to apply when eccentric contractions are produced in vitro and in vivo. The magnitude of increase in force elicited with stretch has been shown to be related to the amplitude and velocity of stretch in isolated muscle preparations (Edman et al. 1978, Ford et al. 1981, Flitney and Hirst 1978, Harry et al. 1990) and in human studies (Thomson and Chapman 1988). Investigations performed in vitro have demonstrated that the elastic contribution to eccentric force production is dependent on activation level (Blange et al. 1972, Bressler and Clinch 1974, Huxley and Simmons 1971). Although this relationship has only been demonstrated in vitro, investigators have suggested that the same viscoelastic muscular properties must exist in vivo (Gulch et al. 1991, Pousson et al. 1990).

Many investigators have noted differences in shape of the in vitro force/velocity relationship compared to the in vivo moment/angular velocity relationship (Caldwell et al. 1993, Colliander and Tesch 1989, Hortobagyi and Katch 1990, Perrine and Edgerton 1978, Prietto and Caiozzo 1989, Rodgers and Berger 1974, Westing and Seger 1989, Westing et al. 1988 and 1991, Wickiewicz et al. 1984). Discrepancies between these relationships largely exist on the eccentric side (moment values do not exceed isometric levels or increase with increasing velocity in vivo as occurs in isolated muscle experiments). These discrepancies exist to a lesser extent during concentric muscle activity (in vivo moment values do not drop off in a steep hyperbolic fashion with increasing velocity as is suggested by force/velocity data). Various researchers have proposed that a neural regulatory mechanism may influence maximal moment generation in vivo, limiting the development of maximal muscle tension and therefore partially accounting for the differences between force/velocity and moment/angular velocity relationships (Hortobagyi and Katch 1990, Perrine and Edgerton 1978, Prietto and Caiozzo 1989, Westing et al. 1988 and 1991).

Neural Regulation

Perrine and Edgerton (1978) postulated that maximum voluntary moments produced during isometric and low velocity concentric contractions might be restricted to approximately 50% of the levels predicted by in vitro studies by a neural regulatory mechanism. It has been suggested that this tension-limiting mechanism might limit the generation of moment to maximum "safe" levels in vivo (Perrine and Edgerton 1978, Stauber 1989, Westing et al. 1988 and 1991).

Limited activation in vivo may explain some of the discrepancies demonstrated between the force/velocity and moment/angular velocity relationships Controversy exists in the literature as to whether humans are capable of fully activating all motor units during voluntary contraction (as would occur in the in vitro experiment). In his review, Sale (1988) stated that in general, healthy individuals are able to fully activate all motor units during voluntary isometric contractions. However, Sale also stated that considerable intersubject variability exists and that some muscles are more easily fully activated than others. Belanger and McComas (1981) also reported that voluntary motor unit activation varied between muscle groups and may be incomplete. These investigators used twitch interpolation to deliver a supramaximal stimulus to the nerve of the muscle(s) engaged in a maximal voluntary isometric contraction. With this technique, an increment appears in the force output when the stimulus is applied if all motor units have not already been fully voluntarily activated. Using voluntary strength tests and the interpolated twitch technique, Belanger and McComas discovered that the ankle dorsiflexors could be relatively easily maximally activated voluntarily, but that maximal activation of the plantarflexors could not be achieved voluntarily. The same technique described by Belanger and McComas was used by Blimkie and co-workers (1990) to determine percentage of motor unit activation during isometric knee extension in adolescent males. Results showed that subjects were voluntarily able to reach 85 to 95% of maximal activation levels. Sale et al. (1992) used the interpolated twitch technique and reported voluntary activation levels of 75-85% for isometric knee extension in 8 young men which did not change after a 19 week weight training program. In contrast, the investigation by Chapman et al. (1984) demonstrated no increase in external force when interpolated twitch was applied during maximal voluntary isometric contraction of the knee extensors which suggests that full activation was achieved voluntarily.

Although the twitch interpolation technique has been used to gain insight into voluntary activation levels during isometric contractions, very few studies have attempted to study relative levels of activation during dynamic eccentric contractions. Researchers have suggested that reduced drive to agonist muscles undergoing high-tension loading during eccentric contractions may protect the musculoskeletal system from injury that could result if the muscles were allowed to become fully activated under these conditions (Stauber 1989, Westing et al. 1988 and 1991). Although direct physiological evidence of a neural regulatory mechanism is lacking, it has been postulated that it is likely a result of complex interactions among several afferent and efferent signals possibly including feedback from free nerve endings in muscle, Golgi tendon organs, joint receptors, cutaneous receptors and pain receptors (Westing et al. 1991).

Some studies have superimposed electrical stimulation on voluntary contractions and compared moment generation under superimposed electrical stimulation to that produced voluntarily to determine and compare relative activation levels during eccentric, concentric and isometric contractions (Dudley et al. 1990, Westing et al. 1990). It is assumed that electrical stimulation can activate the vast majority of motor axons resulting in full contraction of the muscle. Electrically-evoked muscle moments should therefore represent the uninhibited capacity of muscle (Westing et al. 1990, Westing et al. 1991). Westing and colleagues (1990) examined the effects of electrical stimulation on knee extensor moment output in nine male athletes at velocities of 60, 180 and 360 °/s. Maximal voluntary contractions, electrically evoked contractions and voluntary contractions with superimposed electrical stimulation were studied. Stimulation was applied transcutaneously at 50 Hz. and at the maximum tolerated voltage which reportedly approached 90% MVC. Mean angle-specific knee extensor moments measured at 60° of knee flexion were used for comparison among concentric, eccentric and isometric contractions. Maximal angle-specific voluntary eccentric moments increased significantly by an average of 21-24% when electrical stimulation was superimposed whereas superimposed moments were not significantly greater than maximal voluntary moments under isometric or concentric conditions. Electrically evoked moments exceeded voluntary moments under eccentric conditions (11-12%, $p<0.05$), but were less under isometric and concentric testing conditions (-10 to -52%, $p<0.05$). Mean angle-specific eccentric moments generated voluntarily remained at the isometric level whereas electrically superimposed moments were significantly greater than isometric levels (20-23%, $p<0.05$). Both voluntarily generated and superimposed eccentric moments were not significantly different over the 3 testing velocities whereas electrically evoked eccentric moments increased from 60 to 360°/s (5% change, $p<0.05$). Based on their results, Westing and coworkers concluded that human muscle has greater potential for moment production than can be elicited voluntarily. They proposed that a neural inhibitory mechanism exists which may limit the musculoskeletal system from producing extreme levels of tension that could otherwise develop under conditions of full activation.

Dudley et al. (1990) also used electrical stimulation to study concentric, isometric and eccentric knee extensor moment generation in 8 NWT adults. Maximal voluntary strength tests were performed over 9 velocities ranging from 10-210 °/s. Angle-specific moments were recorded at an actuator arm angle of 45° below horizontal. Tests were also performed under transcutaneous tetanic electrical stimulation that induced an isometric moment equal to 60% MVC (STIM 1) or 45% MVC (STIM 2). In contrast, the electrically evoked isometric moments in the study by Westing et al. (1990) reportedly approached 90% MVC. Despite this difference, Dudley and colleagues demonstrated a significant increase in moments to 1.4 times maximum voluntary isometric maximum with increasing speed of eccentric contractions from 0 to 90°/s for STIM 1 and STIM 2 conditions. (Whereas Westing and coworkers demonstrated that eccentric moments were only 1.11-1.12 times maximal voluntary isometric moments). Eccentric moment values did not increase with further increases in velocity in the study by Dudley and colleagues. Maximal voluntary eccentric moment values remained at isometric levels over all velocities. As velocity increased from 0 to 210°/s for concentric tests, moments decreased significantly more under STIM 1 and STIM 2 conditions (decreased by 67%) than under voluntary activation (decreased by 50%). Based on these results, Dudley and coworkers were able to show that the shape of the moment/angular velocity relationship for the knee extensors more closely resembled the shape of the classic force/velocity relationship when electrical stimulation was applied. Based on the fact that greater differences existed on the eccentric side of the voluntary and electrical stimulation moment/angular velocity plots, Dudley and colleagues speculated that neural factors must limit the maximum generation of moment to a greater extent during eccentric activity compared to concentric activity. Dudley and coworkers noted that the increase in moment with increasing eccentric velocity (which then plateaued at 90 °/s) was comparable to relationships determined using isolated muscle (Flitney and Hirst 1978, Joyce et al. 1969). The authors suggested that the factor responsible for these characteristics, namely active series elasticity, could be expressed in situ with artificial stimulation.

Resultant Joint Moment

Researchers have suggested that a neural regulatory mechanism is at least partially responsible for the shape differences in the force/velocity and moment/angular velocity relationships but many other differences exist between in vitro and in vivo test conditions. The voluntary generation of moment about a joint is a consequence of neural, mechanical, and muscular interactions whereas only muscular properties influence isolated muscle force/velocity relationships (Enoka 1988b). Neural factors which influence the voluntary production of moment include the number of motor units activated (size principle), the discharge frequency and the activation pattern (synchrony) of motor units. Muscle moment arm represents a mechanical factor which constantly changes with changes in joint configuration. In the body's rotary system, change in muscle length is trigonometrically related to the angular motion of the segments. As such, the linear velocity of the muscle is not constant during constant angular velocity motion of the segment. However, these factors alone do not explain the large differences demonstrated between eccentric and concentric moment/angular velocity and force/velocity relationships. Many properties intrinsic to muscle can influence the production of moment. The physiological cross-sectional area of involved muscles, the types of muscle fibres comprising the activated motor units, the length of involved muscles at the time of measurement (force-length relationship) and the rate of change of muscle length (force/velocity relationship) all affect the production of moment. Coactivation of antagonistic muscle groups may also effectively reduce the moment generated by the agonist groups.

The resultant joint moment (RJM) produced by a subject represents the sum total of all muscular, tendinous, ligamentous, cartilaginous, capsular, and bone-on-bone forces acting about the instantaneous axis of rotation of the joint (Hay 1992). Passive stretching of muscle, tendon, and ligament tissue or abrasion of roughened articular surfaces may all influence the magnitude of moment produced. The generation of a moment about a joint involves the activation of more than one muscle and more than one muscle group (Baratta et al. 1988, Hay 1992, Solomonow et al. 1987 and 1988). Studies have demonstrated that variable coactivation of antagonistic muscle groups occurs throughout range of motion (Baratta et al. 1988, Solomonow et al. 1988). The RJM is estimated by the moment recorded by the dynamometer during voluntary isovelocity strength tests. However, the RJM produced by the subject does not equal the moment measured on the isovelocity dynamometer (Herzog 1988, Sapega et al. 1982, Winter et al. 1981). Accurate interpretation of results requires an appreciation for the limitations of isovelocity dynamometry. Gravitational effects, inertial effects, non-rigidity of the actuator arm/human limb segment system, stabilization and axial alignment issues can all affect the measurement of moments by an isovelocity dynamometer (Appen and Duncan 1986, Fillyaw et al. 1986, Gransberg and Knutsson 1983, Hart et al. 1984, Herzog 1988, Nelson and Duncan 1983, Nosse 1982, Osternig 1986, Rothstein et al. 1987, Winter et al. 1981). Herzog (1988) showed that relative movement exists between the actuator arm and the limb segment and that accelerations of the two are not equal. The dynamometer only detects forces exerted perpendicular to its force transducer. Because a joint's instantaneous axis of rotation changes with changes in joint angle (Smidt 1973), it is impossible to achieve constant coaxial alignment. It is important, however, to strive for consistent alignment of the limb segment with the dynamometer prior to each trial. Dynamometers measure moment based on the assumption that static equilibrium exists (where the sum of all moments equals zero). Therefore, moments recorded during the acceleration and deceleration portions of movement are not accurate (Osternig 1986). The constant velocity (i.e. negligible acceleration) portion of the tested movement has been shown to decrease in size with increasing angular velocity of testing (Perrine and Edgerton 1978).

Considering the complex interaction between neural, mechanical and muscular factors which influence the voluntary generation of moment, it is understandable that the moment/angular velocity relationship does not resemble the force/velocity relationship. Force/velocity properties exist for all activated muscles during functional human movement and exert a combined influence on the RJM. In addition to the other neural, mechanical and muscular factors already discussed, the age of the participant and the diversity of the methodology employed in isovelocity testing (capabilities of dynamometers used; length of time delay between concentric and eccentric muscle actions; method used for correction for moment of the weight of the leg, foot and actuator arm; choice of velocities used in testing, and the criterion measure of moment) have also been shown to affect the moment/angular velocity relationship (Griffin et al. 1993, Harries and Bassey 1990, Poulin et al. 1992, Stanley and Taylor 1993). Caldwell and co-workers (1993) noted that the characteristic moment/angular velocity relationship for any particular muscle group is the result of a weighted combination of neural, mechanical and muscular factors and that the relative weighting of these factors dictates the shape of the resultant joint moment/angular velocity curve. Caldwell and colleagues recognized that these factors could counteract the effects of each other, possibly producing similar resultant joint moment/angular velocity relationships from very different underlying physiological mechanisms.

Neural Adaptations with Training

Investigators have suggested that the degree of neural regulation influencing moment generation may be dependent on an individual's absolute strength level (Caiozzo et al. 1981, Hortobagyi and Katch 1990). Hortobagyi and Katch demonstrated that the shape of moment/angular velocity relationships for the elbow flexors and extensors varied on the concentric and eccentric sides depending on the subject's absolute strength level. Eccentric moments exceeded concentric moments in both groups. However, eccentric and concentric moments did not change with changes in velocity of testing in the low strength group. Eccentric moments increased with increasing velocity of testing and concentric moments decreased with increasing velocity of testing in the high strength group. Caiozzo and coworkers examined changes in the concentric moment/angular velocity relationship in subjects who trained the knee extensors concentrically at different velocities for 4 weeks. Concentric isovelocity strength tests were performed over 7 velocities ranging from 0-290°/s. Subjects who were trained at 96°/s demonstrated significant increases (5-15%) in angle-specific moments at all but the greatest velocity. Absolute increases in moment were greatest at the lower velocities such that training increased the slope of the moment/angular velocity relationship in resemblance of the classic force/velocity relationship for isolated muscle. Caiozzo and colleagues suggested that training may have decreased the influence of the inhibitory neural mechanism said to be responsible for plateauing of the concentric moment/angular velocity curve at lower velocities. Because subjects who trained at 240°/s demonstrated significant increases in moment values only at the higher velocities of 144, 192 and 240°/s, the investigators proposed that a different mechanism (other than reduction of neural inhibition) may have been responsible for their training response. No significant changes were seen in the control group.

Sale (1988) in his review of neural adaptation and resistance training stated that "strength training may cause adaptive changes within the nervous system that allow a trainee to more fully activate prime movers in specific movements and to better coordinate the activation of all relevant muscles, thereby effecting a greater net force in the intended direction of movement." EMG studies have demonstrated that recorded motor unit activation levels are increased, reflex potentiation is enhanced and motor unit discharge synchronization is enhanced with resistance training (as reviewed in Sale 1988). Weight training has been shown to induce increases in voluntary strength with little or no hypertrophy, cause "cross-over" strengthening in the limb contralateral to the trained limb and produce increases in voluntary strength specific to the type of contraction, joint angle and velocity of movement (Kannus et al. 1992, Sale 1988). These findings suggest that some increases in strength are related to neural adaptations such as improved coordination and increased activation of involved musculature (Jones 1992, Rutherford and Jones 1986, Thorstensson et al. 1976). After an extended period of regular strength training these neural adaptations may partially over-ride the tension-regulating mechanism proposed to limit moment production during maximal voluntary contractions.

Mechanical and Muscular Adaptations with Training

Besides its effect on neural control, resistance training has also been shown to affect intrinsic muscular properties such as muscle cross-sectional area (Alway et al. 1990, Goldspink 1992, Jones 1992), muscle length (Jones et al. 1992) and the relative volume of different fibre types within involved muscles (Schantz and Kallman 1989, Staron et al. 1989, Thorstennson et al. 1976). It has been suggested that the large increases in muscle mass associated with training might alter mechanical properties governing moment generation capacity such as the muscle moment arm length/joint angle relationship (c.f. Jones et al. 1992, Tsunoda et al. 1993) and the alignment of the muscle fibres relative to the line of pull of the tendon (Jones et al. 1992, Kaufman 1989, Tsunoda et al. 1993). Given that the neural, mechanical and muscular properties governing production of RJM differ between WT and NWT individuals, moment/angular velocity and moment/angle relationships may be used to characterize differences in strength related to resistance training.

Quantifying Strength

Strength can be defined as "the ability of the neuromuscular system to control rotation of body segments" (D. Kriellaars, personal communication, 1993). Functional actions performed by humans require the generation of muscular moments to produce and/or control motion of the body's segments.

Moment/angular velocity relationships for the knee musculature

Peak moments and angle-specific moments have been the most frequently measured strength parameters recorded during isovelocity tests. Peak moment and angle-specific moment represent moment generating capability at one joint angle within the selected range of motion (typically 90° range of motion for the knee joint). Generally, the mean value of peak moment or angle-specific moment recorded over a number of repetitions has been plotted against the angular velocities included in testing (typically 3 speeds for concentric tests and less frequently, 3 speeds for eccentric tests) to generate moment/angular velocity relationships for the muscle group in question. Maximum isometric moments generated by the knee extensors have been shown to exceed maximum concentric moments which decrease with increasing velocity of shortening (Alexander 1990, Caldwell et al. 1993, Perrine and Edgerton 1978, Prietto and Caiozzo 1989, Taylor et al. 1991, Thorstennson et al. 1976, Westing et al. 1988). Concentric knee extensor moments have been shown to decrease with increasing velocity of testing when both peak moments and angle-specific moments are plotted against velocity (Caldwell et al. 1993, Westing et al. 1988). Maximum eccentric moments for the knee extensors have been shown to reach magnitudes equal to maximum isometric moment and to remain at the same magnitude with changes in velocity of testing (Dudley et al. 1990, Lacerte et al. 1992, Westing and Seger 1989, Westing et al. 1988, Westing et al. 1990). Similar moment/angular velocity relationships have been demonstrated for the knee flexors (Caldwell et al. 1993, Colliander and Tesch 1989, Prietto and Caiozzo 1989), however, the knee flexors have generally demonstrated a less dramatic decrease in moment values with increasing velocity of concentric testing compared to the knee extensors (Caldwell et al. 1993, Colliander and Tesch 1989, Richards 1981, Wickiewicz et al. 1984).

Unlike the results of the elbow strength study by Hortobagyi and Katch (1990) which suggested that the relative shape of eccentric and concentric moment/angular velocity relationships varied depending on individual differences in strength, knee extension and flexion studies have not demonstrated any deviation from the typical moment/angular velocity plot shape. Alexander (1990) demonstrated that body mass normalized concentric knee extensor and flexor moments measured in elite sprinters decreased with increasing velocity of testing, whereas eccentric moments remained relatively constant with change in velocity. Brown and Wilkinson (1983) demonstrated that concentric knee extensor moments decreased with increasing velocity of testing independent of whether subjects were national, divisional or club level alpine skiers. Taylor and colleagues (1991) measured knee extensor angle-specific moment (at 60° knee flexion) and peak moment during concentric isovelocity tests performed at 12 angular velocities spanning 30°/s to 300°/s over a 90° joint range of motion. Subjects included 6 elite power athletes (Olympic and power weight lifters, sprinters and volleyball players) and 7 endurance athletes (middle and long distance runners, distance cyclists and triathletes). Results demonstrated that the power athletes generated greater peak and angle-specific moments than the endurance athletes at each testing velocity. However, both groups experienced equivalent moment decrements over the range of test velocities and the shape of the concentric moment/angular velocity relationship did not differ between groups.

Moment/angle relationships for the knee musculature

Moment/angle relationships which depict the moment generating capability of the muscle groups throughout the tested range of motion have been much less frequently reported than moment/angular velocity relationships for the knee musculature. Typically, the peak moment or the moment recorded at a specified joint angle (angle-specific moment) is determined from the moment/angle plot and is then used to depict the moment/angular velocity relationship. However, some researchers have included moment/angle relationships in their results. Most commonly, the moment/angle relationship has been documented for the isometric condition (Bobbert and Harlaar 1992, Caldwell et al. 1993, Knapik et al. 1983). It is important to note that all data points plotted on an isometric moment/angle graph were recorded during different repetitions of the isometric contraction at different joint angles. Isometric moment/angle plots for the knee extensors have demonstrated that the moment values form a smooth curve, the apex of which (i.e. the maximum isometric moment) occurs between 65° and 85° of knee flexion (Bobbert and Harlaar 1992, Caldwell et al. 1993, Knapik et al. 1983, Westing et al. 1988). Strength tests for knee flexion have demonstrated that maximum isometric moments occur between 20° and 30° of knee flexion (Caldwell et al. 1993). The shape of the knee flexion isometric moment/angle relationship is much flatter than that demonstrated for the knee extensors (Caldwell et al. 1993).

Mean moment/angle plots for a group of subjects and individual moment/angle plots recorded during isovelocity strength assessments have also been included in some study reports (Bobbert and Harlaar 1992, Hoke et al. 1983, Koutedakis et al. 1995, Knapik et al. 1983, Trudelle et al. 1989, Westing and Seger 1989, Westing et al. 1990). Moment/angle plots presented for eccentric and concentric tests represent the moment generating capability over the tested range of motion at one specific speed of movement. In general, the concentric and eccentric knee flexor and extensor moment/angle plots have all demonstrated a curved shape with their respective maximum moments occurring at different joint angles depending on the muscle group tested, the velocity of testing and the type of contraction (Baltzopoulos and Brodie 1989, Thorstennson et al. 1976). Moment/angle plots for the knee flexors generally tend to be flatter than the curves demonstrated for the knee extensors (Westing and Seger 1989). The shape of these curves is also dependent on the joint range of motion included in testing and on the force level required to be attained by the subjects before the dynamometer will begin movement (Osternig 1986). Differences between knee flexor and knee extensor moment/angle curve shapes and magnitudes have been explained based on the different muscle cross-sectional area properties, force-length characteristics, changing muscle moment arms and activation strategies (Herzog et al. 1991, Wickiewicz et al. 1983).

Some investigators have suggested that visual analysis of the shape of the moment/angle and moment/angular velocity curves measured during isovelocity strength assessments may be useful in determining the diagnosis and prognosis of certain conditions which affect strength (Afzali et al. 1992, Hoke et al. 1983, Koutedakis et al. 1995). However, visual inspection and analysis of these relationships is still very much a subjective process. Preliminary attempts to accurately represent the shape of moment/angle curves by fitting mathematical formulae to data have not been widely accepted (Afzali et al. and commentary 1992).

Comprehensive Analysis of Strength

Strength can be defined as the ability to control rotation of the body's segments through the generation of moments about joints. Isovelocity dynamometers have been used to objectively quantify moments produced during single segment motion. However, peak moments and angle-specific moments have been the most frequently reported strength parameters. Analyses of these parameters alone may fail to capture relevant information that could be gained from more elaborate and comprehensive data processing and testing. Comprehensive depiction and quantification of moment generating capabilities during different types of contractions (isometric, concentric and eccentric), at different speeds of movement and throughout the range of motion are required to provide for more complete strength analysis. Just as the force/velocity/length relationship has been used to precisely describe performance of muscle in vitro (Coirault et al. 1994), moment/angle and moment/angular velocity relationships could be depicted together as the three dimensional moment/angle/angular velocity relationship. The moment/angle/angular velocity relationship could be used to qualitatively and quantitatively portray maximum moment generating capability throughout the range of motion and for all speeds and contraction types included in human strength assessment.

Because the generation of resultant joint moment involves the activation of many muscles (agonist and antagonist to the movement being performed) with each muscle's contribution to the overall moment influenced by neural, mechanical, and intrinsic muscular properties, one would expect the moment generating characteristics for specific muscle groups and specific movements (e.g. knee extension) to be represented by unique moment/angle/angular velocity relationships. Depiction of the moment/angle/angular velocity relationship for the knee flexors and knee extensors in WT and NWT individuals may allow for more comprehensive analysis of strength differences than can be captured with the strength analysis techniques currently used. However, many studies have suggested that it is not maximum moment values that should be compared between subjects habituated to different levels of physical activity (e.g. athletes versus controls or patients versus controls) but rather it is the balance of strength between reciprocal muscle groups or across contralateral limbs that is important (Appen and Duncan 1986, Alexander 1990, Figoni et al. 1988, Grace et al. 1984, Griffin et al. 1993, Murray et al. 1984, Nosse 1982). Researchers and clinicians have speculated that detection of "abnormal" ratio values may give insight into the existence of muscular imbalances which may predispose certain individuals to injury or may be indicative of inadequate rehabilitation post-injury or post-surgery (Baltzopoulos and Brodie 1989, Brink and Stoner 1995, Dvir 1995, Grace et al. 1984, Grace 1985, Janda 1993, van Mechelen 1992, Yamamoto 1993). Muscular strength imbalances have been proposed to be causatively related to the development of rotator cuff impingement (Burnham et al. 1993), anterior shoulder instability (Glousman 1993, Bradley and Tibone 1991), injuries to the anterior cruciate ligament (Baratta et al. 1988) and hamstring strains (Yamamoto 1993). However, attempts to use pre-season isovelocity reciprocal muscle testing to distinguish athletes who may be predisposed to develop injury have been largely unsuccessful and the functional significance of these ratios has been questioned (Grace et al. 1984, Grace 1985, Rothstein et al. 1987).

The hamstring/quadriceps or knee flexor/extensor peak moment ratio has been reported to take on a wide range of values (from 0.43 to 0.90) in the literature depending on the population studied (age, gender, type of athletic participation, specific injury diagnosis), the protocol used (positioning, range of motion, velocity), and the types of contractions analyzed (Alexander 1990, Appen and Duncan 1986, Burnie 1987, Dibrezzo et al. 1985, Figoni et al. 1988, Griffin et al. 1993, Hageman et al. 1988, Holmes and Alderink 1984, Nosse 1982, Osternig 1986, Stanley and Taylor 1993). Nosse in his review noted that the knee flexor/extensor ratio of 0.60 which has gained wide acceptance as being representative of "normal knee flexor/extensor muscle balance" was originally attained under isometric testing conditions at 15° and 65° of knee flexion respectively in young male football players. Nosse cautioned that this 0.60 ratio value was unique to the conditions under which it was tested and would not necessarily be representative of knee muscle balance when testing involved a different group of individuals, different isometric test angles, different contraction types (concentric and/or eccentric contractions) and different speeds of contraction.

Because the moments produced by reciprocal muscle groups are bound by neural, muscular and mechanical factors which affect all muscles activated in a movement, the strength relationship between reciprocal muscle groups is not static. Within a muscle group activation levels vary and the pattern of activation may change throughout the range of motion. These same factors influence coactivation levels of antagonist muscle groups. Peak moment has been shown to occur later in the range of motion with increasing velocities (Kannus and Beynnon 1993, Lord et al. 1992). The relative change in angle of peak moment occurrence with change in testing velocity has been shown to be different for the knee flexors and knee extensors (Kannus and Beynnon 1993). For these reasons, some investigators have used angle-specific moments to generate knee flexor/extensor ratios (Prietto and Caiozzo 1989). In this study, the knee flexor moment/angle/angular velocity relationship shall be matched for velocity, joint angle and contraction-type and expressed as a ratio of the knee extensor moment/angle/angular velocity relationship in attempt to gain further insight into the balance of strength which exists between these muscle groups about the knee.

Summary

In summary, it has been shown that human moment/angular velocity relationships do not resemble force/velocity relationships established in isolated muscle investigations. Eccentric force has been shown to reach 1.5 to 1.9 times maximum isometric force when a stretch is applied in vitro. However, maximum voluntary eccentric moments generated in vivo do not exceed maximum isometric moment. The increase in force produced during eccentric contractions is believed to be largely related to muscle series elasticity which in isolated muscle has been shown to be dependent on the velocity of stretch, amplitude of stretch and degree of activation of muscle. A direct relationship between the level of neuromuscular activation and the enhancement of moment during eccentric contraction has yet to be demonstrated in human studies. It has been proposed that a neural regulatory mechanism limits maximal voluntary activation during lengthening contractions and that the degree of neural regulation may vary between trained and untrained individuals. However, quantification of the relative degree of neural regulation influencing eccentric moment generation has not been investigated in subjects of different training backgrounds. Besides influencing neural factors, training also affects mechanical and intrinsic muscular factors which influence the generation of RJM. Analysis of moment/angle/angular velocity relationships for subjects of different training backgrounds will provide detailed information about differences in strength related to training.

Purpose

The purpose of this study was to examine the eccentric side of the moment/angular velocity relationship and to contrast the magnitudes of voluntarily generated eccentric moments with those produced involuntarily and with minimal reflex contribution. The relationship between pre-perturbation isometric moments and the resultant imposed eccentric moments was investigated to gain further understanding of the actomyosin dependent elastic contribution to eccentric moment generation in vivo. In addition, concentric, eccentric and isometric strength of the knee extensors and flexors was evaluated in NWT and WT males in order to examine possible differences in neural control, mechanical factors and intrinsic muscular factors associated with training.

Objectives

1. To examine the contribution of actomyosin-dependent elasticity to eccentric moment generation in vivo by determining the relationship between different pre-perturbation isometric moments and the imposed eccentric moments which result when forced-lengthening occurs. This relationship shall be evaluated in a WT male group and in a control group of NWT males.

2. To determine the relationship between the magnitudes of maximum isometric moments and predicted maximum imposed eccentric moments for the knee extensors and to compare this relationship to reported in vitro force-velocity relationships and the in vivo moment/angular velocity relationship of the WT and NWT groups.

3. To compare maximum voluntary eccentric moments to predicted maximum imposed eccentric moments for the knee extensors (at the same angular velocity and at the same joint angle) to quantify the degree of neural regulation present during voluntary eccentric contractions. The quantified neural regulatory influence shall be compared between WT and NWT male groups.

4. To determine and compare isometric, eccentric and concentric strength of the knee flexors and extensors in a group of WT males and a control group of NWT males through analysis of moment/angle/angular velocity relationships.

Hypotheses

1. The magnitude of the imposed eccentric moment will be linearly proportional to the magnitude of the preceding isometric moment. This linear relationship will not be significantly different for the WT and NWT groups.

2. A substantial degree of neural regulation will exist and limit moment production during voluntary eccentric contractions as compared to involuntary imposed eccentric contractions. The relative degree of neural regulation (indicated by the difference between the predicted maximum imposed eccentric moment and the moment recorded during the voluntary strength test at the identical joint angle and velocity of testing) will be less in the WT group than in the NWT group.

3. The shape of the knee extensor and knee flexor moment/angle/angular velocity relationships shall differ in the following ways for both groups.

   3.1. Peak moments shall occur in different quadrants of the moment/angle/angular velocity strength map (i.e. at different joint angles in the tested range of motion).

   3.2. The slope of the decline in concentric knee flexor moments with increasing velocity of testing shall be less than that for the knee extensors.

4. The magnitude and shape of the knee extensor and knee flexor moment/angle/angular velocity relationships shall differ between WT and NWT subjects.

   4.1. The WT group will demonstrate greater strength than the NWT group for knee flexors and extensors over most of the strength domain as depicted in the moment/angle/angular velocity relationships. Specifically, the greatest difference in strength will exist around the isometric and low velocity concentric and eccentric regions of the moment/angle/angular velocity strength map consistent with the specific effects of weight training.

4.2. The slope of the concentric moment/angular velocity relationship shall not be significantly different for the NWT and WT groups.

4.3. The difference between peak eccentric moments and peak concentric moments shall be greater in the WT group compared to the NWT group.

Clinical Relevance

Further understanding of the mechanisms responsible for moment generation during eccentric contraction may provide more information about the association between eccentric contraction and the development of delayed onset muscle soreness and/or tendinitis, as well as the ability to influence eccentric moment generation through therapeutic or preventative methods. Recognition and quantification of the elastic contribution to eccentric moment generation may be used to assist in the development of or modification of strength training programs and rehabilitative exercises. Comprehensive analysis of knee extensor and flexor strength in terms of moment generation during different types of contractions, at different speeds of movement and throughout the tested range of motion will contribute to our understanding of muscle balance about the knee and strength differences that exist in WT and NWT individuals. Analysis of relationships between maximum voluntary isometric, concentric and eccentric moment generating capabilities may provide information useful in for prediction of injury potential based upon strength screening assessments, the development and progression of strength training for uninjured and injured workers or athletes.

Delimitations

This study examined male subjects 20-45 years of age. The NWT group included only individuals who had not participated in any specific lower extremity strengthening program and had not participated in elite/competitive sports within the last 5 years. The WT group included only individuals who participated in a strengthening program greater than 2 times/week which included resisted knee extension and knee flexion exercises. Only WT individuals who also reported that they were able to full squat (knee joint flexion 90° or greater) greater than or equal to 150% body weight during a 1 Repetition Maximum Test (1RM) were included in the study.

Isovelocity measurements were delineated to those taken with the hip position assumed when the backrest was reclined 15° from vertical. Step test measurements were delimited to the velocity of 100°/s and the range of motion of 60-72° of knee flexion. Velocity spectrum strength testing was delimited to the testing velocities of 50, 100, 150, 200 and 250°/s and examined only the movements of knee flexion and extension. The knee flexor and extensor isometric strength tests were each delimited to one joint angle (isometric knee flexion at 25°, isometric knee extension at 70°).

Limitations

Imposed eccentric knee extensor moments recorded during the step test at 100°/s over 60-72° of knee flexion did not provide direct information about eccentric muscle performance at other velocities, at other points within the range of motion or about other muscle groups. Analysis of moments was restricted to single segment motion in this study which is not necessarily representative of neuromuscular activity during functional multi-segmental motion. The spectrum of velocities tested (0-250°/s) in this study represented a small portion of the spectrum of angular velocities encountered during functional activities. Isovelocity strength testing was dependent on the subject being able to provide maximal effort during the voluntary contractions.

Assumptions

The primary assumption made in this study was that the moment recorded by the dynamometer accurately represented the RJM about the knee. This assumed that co-axial alignment was maintained between the axis of rotation of the knee joint and the axis of rotation of the actuator arm, that segmental stabilization was adequate to minimize the relative movement between the actuator arm and the limb segment, that the knee flexor and extensor moments produced by the subjects were generated wholly in the direction perpendicular to the force transducer of the dynamometer throughout the range of motion and that inertial effects were negligible (Herzog 1988).

This study further assumed that the imposed eccentric moments recorded during the step test did not contain a significant stretch reflex evoked response (Burke et al. 1970, von Kampen 1996) and that residual tone in the hamstring and quadriceps muscles did not affect the moment of the weight of the leg, foot and resistance pad measurements. It was assumed that at 45° of flexion, the moment due to passive recoil of the knee flexor and extensors would be zero. It was also assumed that hamstring co-activation levels were relatively equal during voluntary and imposed eccentric contractions of the knee extensors and that neglecting to correct for the moment of the weight of the leg, foot and resistance pad between 95° and 90° degrees of knee flexion did not significantly affect the accuracy of knee extensor or knee flexor moments.

It was assumed that the WT and NWT male subjects included in this study were representative of the general population of physically active males between 20-45 years of age.

Methodology

Subjects

A cross-sectional design was employed where two groups of 15 male subjects were recruited. One group was designated as weight-trained (WT) and the other as a physically active but non weight-trained group (NWT). A power analysis was used to determine the number of subjects for the study (Appendix A).

Inclusion Criteria

Male subjects between the ages of 20-45 years were included in the study. Subjects were included in the WT group if they participated in lower extremity weight training which included both resisted knee extension and flexion exercises more than twice/week and had been involved in this type of program for at least one year previous to the study. For inclusion in the WT group, subjects had to report that they were able to full squat a minimum of 150% of their body weight during one repetition maximum (1RM).

Exclusion Criteria

Subjects were excluded if they had any history of serious injury to the dominant lower extremity, any restriction in range of motion of dominant lower extremity, or a current injury or disease affecting the non-dominant lower extremity. Exclusion criteria also included known cardiovascular disease or any other medical conditions which might preclude involvement in the study (i.e. history of arthritis or other inflammatory conditions affecting the hip, ankle or foot). Subjects for the NWT group were excluded if they reported that they had participated in lower extremity weight training at a frequency greater than twice/week during the past 5 years or if they had participated in elite/competitive sports within the last 5 years.

Recruitment

A sample of convenience was recruited by word of mouth from the Bannatyne Campus and the Fort Garry Campus of the University of Manitoba.

Selection

After being recruited for the study, each subject's appropriateness for participation in the study to ensure conformity with the inclusion and exclusion criteria (Appendices C and D).

Informed Consent

Subjects were required to sign an informed consent form prior to participation in the study. The study paraphrase and informed consent form are included in Appendix B. Ethical approval for the study was received from the Faculty Committee on the Use of Human Subjects in Research, Faculty of Medicine, University of Manitoba.

Instrumentation

Dynamometer

Isovelocity dynamometers have been shown to be capable of providing objective, valid and reliable measurements of knee strength using various testing protocols for concentric, eccentric and isometric contractions (Gleeson and Mercer 1992, Griffin et al. 1993, Harding et al. 1988, Kues et al. 1992).

The Kinetic-Communicator (Kin-Com 500H, Chattecx Corporation, Hixson, TN) isovelocity dynamometer was used in this study to evaluate knee flexor and extensor strength and to perform a test to evaluate the contribution of muscle elastic forces during eccentric muscle contractions, termed the step test. This microcomputer-controlled, hydraulically driven device uses strain-gauge transducers to measure force, a tachometer to determine angular velocity of the actuator arm, and a potentiometer to detect angular displacement of the actuator arm. The mechanical reliability of the Kin-Com has been established (Farrell and Richards 1986, Mayhew et al. 1994). Farrell and Richards (1986) showed the Kin-Com to be highly reliable (reliability index (RI) = 0.999) in static tests of lever arm position and force measurement and in dynamic tests of velocity setting and force measurement (RI = 0.948). Mayhew et al. (1994) compared force, angular position and velocity measurements obtained by the Kin-Com under controlled conditions with simultaneous measurements obtained from external recording systems using known weights, angles and velocities. In all comparisons the measurements of force, angle and velocity were shown to have a coefficient of determination $r^2 > 0.99$. Intraclass correlation coefficients (ICC) for between-day comparisons were calculated to examine the reliability of the measurements recorded on the Kin-Com and those recorded through external means. All ICC were > 0.99 demonstrating a high degree of agreement between test days.

Procedure

All subjects were given uniform instructions regarding the evaluation procedure and equipment prior to initiation of testing. Only the dominant leg was tested. The dominant leg was defined as the one the subject would choose to use to kick a ball (McLean and Tumilty 1993). Body mass (kg) was measured on a standard medical balance scale (Continental). Thigh length (cm) was measured between the anterior superior iliac spine and the superior pole of the patella. Thigh circumference (cm) was measured 2/3 of the distance between the anterior superior iliac spine and the superior pole of the patella. Skinfold thickness was determined using Harpenden calipers (mm, three repetitions) taken from the anterior thigh at the same level as the thigh circumference measurement.

All subjects performed three tests (maximal voluntary isometric contraction or MVC test, step test and isovelocity strength test) on a dynamometer after completion of a warm-up on a cycle ergometer (Monark 818E, Monark AB, Sweden) at a power output of 35 Watts (70 rpm at a resistance of 0.5 kp) for 5 minutes.

Positioning and Alignment

Subjects were seated on the dynamometer with the backrest reclined 15° from vertical. The non-dominant leg was allowed to hang over the seat (the foot did not touch the floor). Straps were secured around the chest, waist, and thigh of the dominant leg to provide a stable position for testing. Subjects were asked to grasp onto the dynamometer seat with both hands. The axis of rotation of the dynamometer was visually aligned with the lateral femoral condyle of the dominant leg when the knee was flexed 90° (full knee extension = 0°). The pad on the actuator arm was then securely fastened to the subject's leg at a comfortable position approximately 5 cm proximal to the medial malleolus. The distance (m, moment arm) from the axis of rotation of the dynamometer to the location of point of application of the force to the force transducer was recorded for each subject.

Encouragement

Consistent enthusiastic verbal encouragement was given during the MVC tests and during the isovelocity strength tests to elicit maximal effort.

MVC Test

The moment of the weight of the leg, foot and resistance pad was first determined at two positions by having the subject relax the leg while the knee joint angle was positioned at 45° and then at 70°. The force (N) was recorded at each position once a consistent value was maintained as the subject relaxed. The moment of the weight of leg, foot and resistance pad (Nm) was established as the product of the force (N) and the moment arm (m) The subject was then asked to perform one MVC of the knee extensors of 5 seconds duration at 70° of knee flexion before proceeding with the step test. A maximal isometric contraction of the knee flexors of 5 seconds duration was performed at 25° of knee flexion immediately prior to the knee flexion isovelocity strength test. The absolute peak moment was recorded during the MVC test.

Step Test

The start and stop angles on the dynamometer were adjusted to 60° and 72° of knee flexion respectively. The speed was set to 100°/s in the flexion direction (from 60° to 72°) and to 30°/s to return the limb to the starting angle of 60°. While the subject generated a specified magnitude of isometric contraction of the knee extensors at 60° knee flexion, a 12° step angular displacement was imposed in the flexion direction at 100°/s. A 4 second pause was provided after the perturbation before the leg was returned to the starting position. This technique of imposing involuntary or forced eccentric contractions was termed the step test. The high acceleration setting was used on the dynamometer with peak angular acceleration near $3000°/s^2$ (Figure 1). The total duration of the perturbation including the acceleration phases (increasing and then decreasing the speed of the limb) was equal to 200 ms (Figure 1).

Each subject was required to perform 10 repetitions of the step test. For each of the 10 repetitions, a specified pre-perturbation isometric moment level was maintained prior to the imposed lengthening (Figure 1). Target isometric levels were pre-calculated based on each individual's knee extensor MVC test and ranged from 5 to 95 % of MVC. Numerical and graphical feedback was provided to assist subjects in attaining and maintaining an isometric moment near the target level. The subjects were instructed to maintain a constant isometric moment near the target value until the perturbation was imposed. The subjects were instructed to relax after the perturbation was completed and while the actuator arm returned the leg to the starting position. The 10 repetitions were performed in 2 sets of 5 repetitions, with a 2 minute rest between sets. Subjects were given 10-15 practice repetitions before recording the 10 test repetitions in order to familiarize themselves with reaching and maintaining target isometric moments prior to imposition of the perturbation.

The musculotendinous tissues about the knee contribute a passive component to the resultant joint moment about the knee (RJM_k). The contribution of this passive component of the soft tissues spanning the knee joint was determined by applying step test perturbations (5 repetitions from 60° to 72° knee flexion) while the subject was relaxed. These perturbations which were imposed while the subject relaxed were recorded prior to the step test described above. A familiarization bout consisting of 5-10 passive perturbations was provided before the 5 test repetitions were recorded. The mean passive moment of these 5 repetitions, determined at the same joint angle as the peak imposed eccentric moment determined from the step test was then subtracted from the RJM_k to partially account for individual differences in the passive resistance of tissues. The magnitude of this passive component was small (2.87 Nm ± 3.20 SD for the WT group and 2.65 Nm ± 2.22 SD for the NWT group).

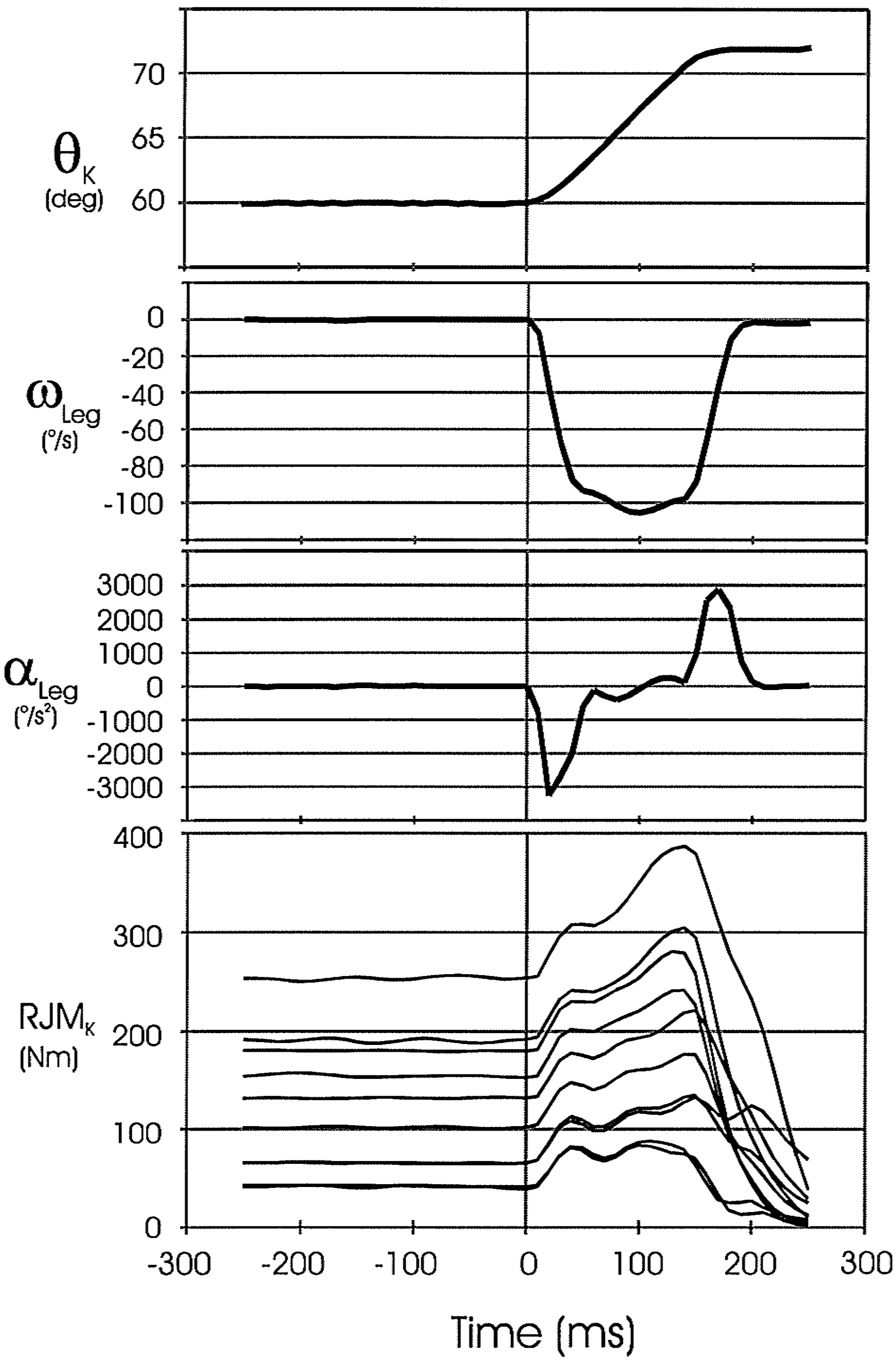

Figure 1. Angular displacement (θ), angular velocity (ω), angular acceleration (α) and resultant joint moment about the knee (RJM_K) plots are shown for a step test of a representative subject. The subject performed the test with ten initial (pre-perturbation) isometric levels ranging from 16.7 to 94.2% MVC. An initial, inertial dependent moment (t = 40 ms) was observed followed by the peak imposed eccentric moment (t = 120 ms).

Graphical feedback for timing of the perturbations was eliminated so that subjects would be less likely to anticipate the onset of the perturbations.

Isovelocity Strength Test

Subjects were systematically allotted to one of four groups for isovelocity strength testing to minimize any order effect due to fatigue. The order of velocity of strength testing for Groups 1 and 3 was 50, 100, 150, 200 and 250 °/s. The order of velocity of strength testing for Groups 2 and 4 was 150, 200, 250, 50 and 100 °/s. Groups 1 and 2 completed concentric and eccentric knee extensor strength tests at each of the above speeds before beginning the knee flexor strength tests. Groups 3 and 4 completed concentric and eccentric knee flexor strength tests at each of the above speeds before beginning knee extensor strength tests.

Isovelocity strength tests consisted of 3 maximal effort concentric and eccentric contractions at 5 speeds as listed above. Strength was measured over a 90° range of motion (5 - 95° of knee flexion). A 4 second pause was provided between successive concentric and eccentric contractions at each velocity. A 2 minute rest was given between test velocities. The medium acceleration setting on the dynamometer was used. Subjects were familiarized to the isovelocity strength tests by performing 3 to 6 sub-maximal effort concentric and eccentric repetitions at each speed prior to testing.

Reliability

Five subjects repeated the isovelocity knee extensor strength test in order to determine the intrarater test-retest reliability for the protocol used in this study. The intra-class correlation coefficient and Pearson's product moment correlation coefficient (r) were calculated for mean peak moments recorded at the ten test velocities. The ICC was equal to 0.865 and r equal to 0.841. A one-way analysis of variance (ANOVA) was performed to determine whether time (initial test or second test) had any effect on the mean moments produced. No significant effect of time was revealed.

Data Collection, Reduction and Analysis

The dynamometer's force transducer, tachometer, and potentiometer are interfaced with an on-board computer equipped with an A/D converter which samples the generated signals at a rate of 100 Hz. The moment arm of the dynamometer was recorded for each subject. Raw data consisting of time, angular displacement, angular velocity, force, and moment arm were exported from the dynamometer's computer. This raw data was then processed using Quattro Pro (Version 6.0) and Isomap Dynamometry Software (Isodyne Inc., Winnipeg, MB). The dynamometer moment (Nm) was calculated as the product of force (N) and moment arm (m). The RJM_k representing the net rotational tendency of all soft tissues spanning the knee was derived by correcting the dynamometer moment for the moment of the weight of the leg, foot and resistance pad.

Angular acceleration was derived from the unfiltered angular velocity waveform by numerical differentiation. Moments generated during concentric contractions were associated with positive angular velocities and moments generated during eccentric contractions were associated with negative velocities.

Correction for the Moment of the Weight of the Leg, Foot and Resistance Pad

For the step test, the moment of the weight of the leg, foot and resistance pad was calculated for each subject while the subject relaxed the leg at 45° of knee flexion. Then the moment of the weight of the leg, foot and resistance pad at the 45° position was trigonometrically converted to other angular positions (60-72° for the step test). The moment of the weight of the leg, foot and resistance pad was added to knee extensor moments (step test, extensor MVC test) and subtracted from knee flexor moments (flexor MVC test). The Kin-Com's "gravity correction" software feature was used to correct for the moment of the weight of the leg, foot and resistance pad for all isovelocity strength tests.

Step Test

For the step test, RJM_k for each imposed eccentric contraction consisted of two peaks (Figure 1). The first peak occurred consistently 40 ms after onset of the perturbation. This was an acceleration-dependent inertial moment, equal to the product of the angular acceleration and the moment of inertia of the leg, foot and resistance pad (Herzog 1988). The peak imposed eccentric moment (second peak in moment trace) was measured during the constant velocity portion of the step response (120-140 ms after onset, 69° knee flexion) for each of the 10 repetitions (Figure 1). The angle of occurrence, time from step onset and absolute value of the peak moment attained during the imposed perturbations was determined for each repetition. The mean passive component of the RJM_k was determined by averaging the values recorded during the 5 passive repetitions. This passive moment was measured at the same joint angle as the peak imposed eccentric moment and was subtracted from the peak imposed eccentric moments to partially account for differences in passive resistance of tissues among subjects. The magnitude of the pre-perturbation isometric moment was determined by averaging the moment data in a 220 ms window just prior to onset of the perturbation. Linear regression was performed between the pre-perturbation isometric moment (independent) and the resultant peak imposed eccentric moment (dependent).

The maximum peak imposed eccentric moment predicted from the step test linear regression equation was compared to the angle and velocity matched, maximum voluntary knee extensor eccentric moment. This comparison was used to reflect the degree of neural regulation during voluntary eccentric contraction.

Strength Parameters

Isovelocity contraction statistics (one reciprocal eccentric and concentric repetition represented 2 contractions) were derived once flatline data (rest time between contractions) was removed using a velocity threshold of ±2°/s. Since the minimum test speed was 50°/s, a velocity threshold of ±40°/s was used to demarcate the start and end of eccentric and concentric contractions.

In addition, an angular acceleration threshold of $\pm 300°/s^2$ was used to identify regions of isovelocity data. Analysis of data was restricted to these regions of non-accelerated (i.e. $< \pm 300°/s^2$) motion. An acceleration threshold of this magnitude would result in an absolute error in RJM_k less than 5 Nm using the standard Newtonian equations of motion and an estimate of the moment of inertia of the leg and foot derived from typical body segment parameter data.

The following parameters were derived automatically using the above criteria: peak moment, angle at peak moment, work per repetition and velocity at peak moment. In addition, the angle-specific moment (at 70° for knee extension tests and at 25° for knee flexion tests) was manually derived from the raw data files. These strength parameters were imported to a spreadsheet (Quattro Pro Version 6.0) along with the raw data files for further analysis. MVC magnitudes were determined using the dynamometer software.

Mean peak moments (average of peak moments from 3 repetitions), absolute peak moments (peak moment with largest magnitude from 3 repetitions) and angle-specific moments (average of moments recorded at 70° during 3 repetitions of knee extension and average of moments recorded at 25° during 3 repetitions of knee flexion) were determined for all concentric and eccentric contractions at all speeds for the knee flexor and knee extensor strength tests.

Strength Maps

Strength maps depict RJM throughout a sampled strength domain (throughout a specified range of motion, during different types of contractions and at different speeds of motion). The three-dimensional moment/angle/angular velocity relationship can be expressed in the form of a two-dimensional relief-type strength map (Figure 2). Strength maps provide objective, quantified, comprehensive and easily interpreted information about moment generating capacity throughout a sampled strength domain.

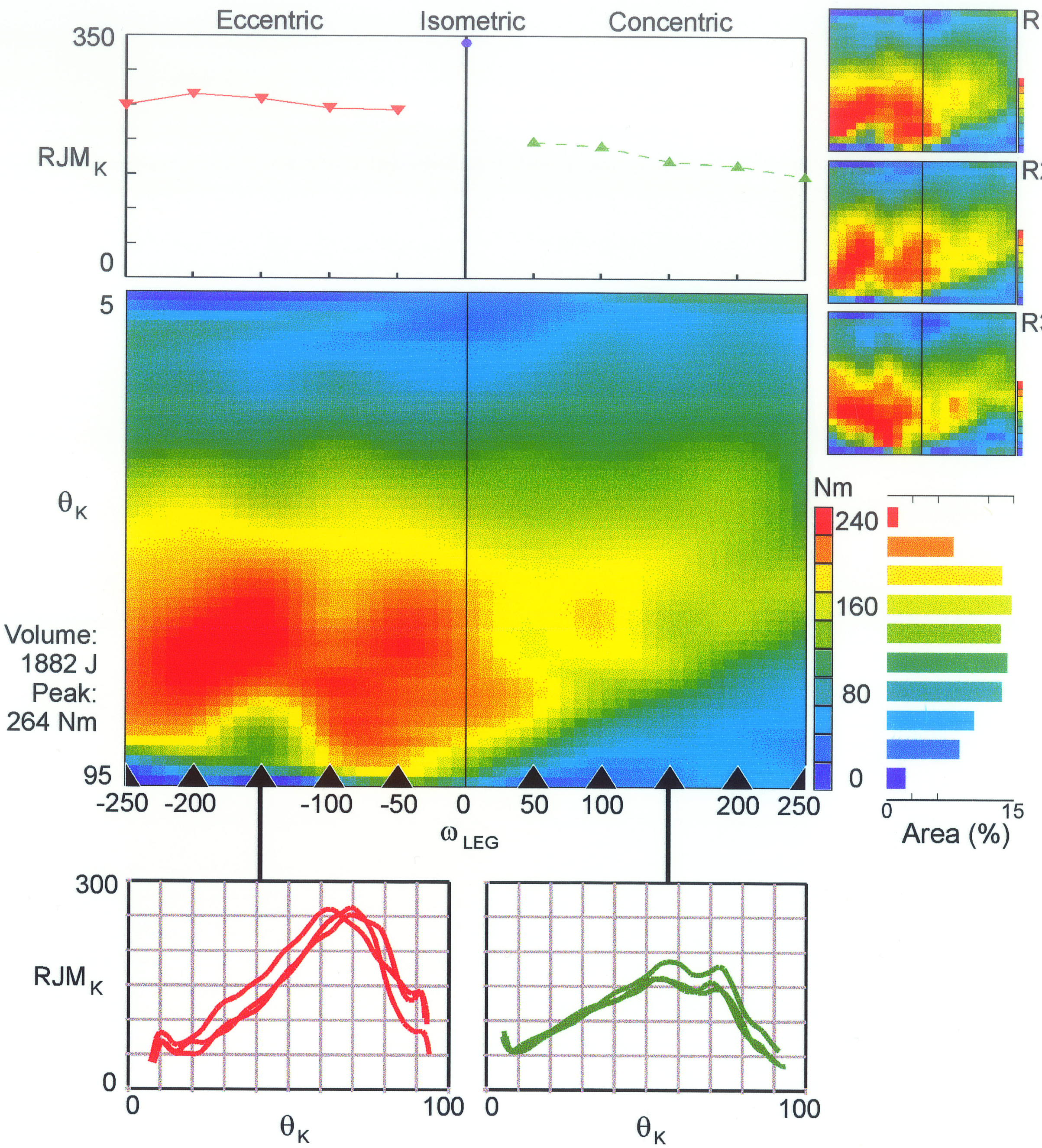

Figure 2. A knee extensor strength map (centre panel) generated from three concentric and eccentric repetitions at 5 speeds (± 50, 100, 150, 200, 250°/s) for a representative subject. The vertical axis is knee joint angle (θ_K; 5 to 95°). The horizontal axis is leg angular velocity (ω_{LEG}; ±250°/s). The color-coded scale bar is the resultant knee joint moment derived from the dynamometer (RJM_K in Nm). The percentage area of the map associated with each color range of RJM_K is shown to the right of the map. The total work (J) corresponding to the volume under the strength map is reported on the left. The peak moment/angular velocity relationship is plotted above the strength map (this is the method commonly used to portray strength data in the literature). Moment/angle plots (bottom panels) showing three repetitions for eccentric (left) and concentric (right) knee extensor muscle contractions for one test speed (±150°/s). The moment/angle data is the raw data used to generate the strength maps. Miniature knee extensor strength maps (top right) were derived for each of the three repetitions (R1, R2, R3). These strength maps depict the between-repetition consistency in strength map topography.

Strength maps were generated from the isovelocity strength tests for knee flexion and extension using Isomap Dynamometry Software. Isomap uses a bicubic interpolating spline to fit all of the concentric and eccentric moment data to a 50 X 50 velocity/angle matrix. For the knee flexor and extensor strength maps the horizontal or x-axes (leg angular velocity) ranged from +250°/s to -250°/s with negative velocities representing eccentric contractions and positive velocities representing concentric contractions. The vertical or y-axes (knee joint angle) ranged from 5 to 95°. The color-coded values or z-axes (RJM_k) values were body mass normalized (Nm/kg), with each relief level (i.e. each different color) representative of a ten percent increment relative to 98% of the maximum moment of the map. This scaling was produced automatically and resulted in consistent graphics which were less sensitive to individual peak moment values. The volume (J) under the moment/angle/angular velocity surface was also calculated and then body mass normalized (J/kg) for each individual knee flexor and extensor strength map. The MVC values were not incorporated into the strength maps because they were only measured at one joint angle for both knee flexion and extension. Therefore, moment data at velocities which were not sampled with the dynamometer are the result of interpolation (for instance, isometric moment data on the maps) and data is extrapolated near the angle boundaries of the map. Knee flexor and knee extensor strength maps were generated for each individual (normalized to body mass). Individual maps were then averaged to produce one body mass normalized map for the knee flexors and one for the knee extensors for each of the WT and NWT groups.

Difference Maps: The knee flexor and knee extensor group "difference" maps were then generated (the average NWT knee flexor map was subtracted from the average WT knee flexor map, average NWT knee extensor map was subtracted from the average WT knee extensor map). Difference maps were generated to allow for regional analysis of strength differences between the groups (strength differences specific to range of motion, contraction type, velocity of movement). The difference maps highlighted regions of greatest difference between the two groups.

Confidence Maps: "Confidence" maps (F or variance ratio maps) were also generated by performing 2500 velocity and angle matched F tests between the WT and NWT average knee extensor maps and average knee flexor maps. In order to make this test more conservative, each velocity and angle matched 1 X 1 grid was accepted as being significantly different only if it was surrounded by at least 6 neighboring (and contiguous) grid squares that were also identified as different and if the total contiguous area of difference was >= 6 squares. The benefit of using a minimum contiguous area of 6 squares is that it provides a means of ensuring that Type I errors are not allowed. The likelihood of having 6 contiguous Type I errors is less than 0.01. This provides ample protection for multiple comparison testing. An F value of 2.40 and an alpha level of 0.05 were used to establish statistical significance of the confidence maps based upon a between group degrees of freedom equal to 9 (10 velocities minus 1) and a within group degrees of freedom equal to 20 (30 subjects minus 10 velocities). It should be noted that the use of confidence maps as an inferential statistical method (rather than descriptive) was still developmental in nature at the time of the study.

Ratio Maps: Knee flexor:extensor ratio strength maps were also generated by dividing the average knee flexor map by the average knee extensor map for both the NWT and WT groups. Contraction-type, velocity and joint angle parameters were matched prior to performing this division to create the ratio map.

Statistical Analysis

1. Statistical analysis was performed using the statistical software program SYSTAT Version 5.0 for Windows and Quattro Pro for Windows version 6.0. The level of significance was set at an alpha level of 0.05.

2. Linear regression analysis was used to determine the relationship between the pre-perturbation isometric moments and the resultant imposed eccentric moments (as a percentage of knee extensor MVC). The linear equations (slope and intercept) for each individual and for each group (NWT and WT) were derived.

3. The predicted maximum imposed eccentric moment (derived from the step test linear regression equation) and the angle-specific eccentric knee extensor moment (measured during the isovelocity strength test at -100°/s) were analyzed for each group (NWT and WT) by means of paired, two-tailed *t* tests. The difference between the predicted maximum imposed eccentric moment and the angle-specific moment (at 70° range of motion and at -100°/s) was calculated for each individual as a measure of the relative degree of neural regulation present during voluntary eccentric contractions. A two-tailed independent *t* test was used to examine differences in moments generated under maximal voluntarily and extrapolated maximal involuntarily conditions, as an indication of the relative degree of neural regulation present in the NWT and WT groups.

4. The group (NWT and WT) and velocity effects on the strength parameters of mean peak moment, angle-specific moment (70° for knee extensors and 25° for knee flexors), absolute peak moment and angle of peak moment occurrence were analyzed by means of a series of two factor or multi-way (group and velocity) analysis of variance. Although, strictly a split-plot or repeated measures analysis of variance is potentially more powerful at resolving differences between groups, a limitation of the analysis software prevented the use of this method. As such, the two factor analysis of variance was performed using an error term which did not consider within subject variation. Each movement (knee flexion and extension) and each contraction type (concentric and eccentric) were analyzed separately using this method.

5. The slopes of the concentric mean peak moment/angular velocity plots for knee extension and knee flexion were determined for the NWT and WT groups. Differences in moment values associated with increasing velocity of testing were analyzed by means of independent (different subject groups) and paired (same subject group) two-tailed *t* tests.

6. The volume of the moment/angle/angular velocity strength maps (body mass normalized) for knee flexion and knee extension were subjected to one-tailed independent *t* tests to analyze for differences between the WT and NWT groups.

7. One-tailed independent *t* tests were used to analyze for differences in knee extensor and knee flexor MVC values between the two groups of subjects.

8. Confidence maps used F ratio calculations to depict regions of difference based upon range of motion and velocity between groups. An F ratio of 2.40 was used to identify regions of difference based on degrees of freedom calculations.

Results

Subject Demographics

A total of 30 male subjects participated in the study; 15 in each of the NWT and WT groups. Group demographics are outlined in Table 1.

Table 1. Group demographics of NWT and WT male subjects. Mean ± SD values are shown where applicable.

	NWT	WT
Number of subjects	**15**	**15**
Age (years)	**27.5 ± 4.5**	**25.1 ± 4.9**
Body Mass (kg)	**76.9 ± 9.3**	**80.6 ± 16.2**
Leg Tested (right:left)	**13 : 2**	**12 : 3**
Thigh girth (cm)	**50.7 ± 3.9**	**52.6 ± 4.3**
Thigh skin-fold (mm)	**8.1 ± 3.4**	**6.1 ± 2.2**
Weight training/week	**0**	**3.7 ± 1.7**
Aerobic training bouts per week	**2.2 ± 1.8**	**2.6 ± 2.5**

Two-tailed independent *t* tests revealed no significant differences between the groups for age, body mass, thigh girth, anterior thigh skin-fold and frequency of aerobic training bouts. None of the subjects in the NWT group reported that they participated in any lower extremity weight-training exercises compared to the WT subjects who performed lower extremity resistance training a mean of 3.7 times per week. Three of the fifteen WT subjects reported that they used performance enhancing drugs.

Post-hoc cross correlations were performed between MVC and body mass (kg), between total knee extensor work (volume of the knee extensor strength map in J/kg) and body mass, and between total knee extensor work and thigh girth (cm) to determine the utility of using normalization to body mass and/or normalization to thigh girth for strength comparisons between groups (Hakkinen et al. 1986, Mayhew et al. 1993). Although group means for body mass and thigh girth were not statistically different in this study, normalization of individual strength values to either body mass or thigh girth still had the potential to affect the results of strength comparisons between the groups. The Pearson's product moment correlation coefficients for MVC and body mass appear in Table 2. Combining the two groups, a correlation coefficient of 0.82 was demonstrated for the relationship between body mass and knee extensor map volume and a correlation coefficient of 0.78 was demonstrated for the relationship between thigh girth and knee extensor map volume. Strength parameters were normalized to body mass for this study based upon the higher r value attained.

Table 2 . Pearson correlation coefficients (r) for isometric moments (MVC) and body mass.

MVC (Nm)	Body Mass (kg)
NWT	
extension	**0.769 p=0.001**
flexion	**0.565 p=0.028**
WT	
extension	**0.720 p=0.002**
flexion	**0.801 p<0.001**

Step Test

The peak imposed eccentric moments and the pre-perturbation isometric moments were expressed as a percentage of MVC (10 repetitions for each subject). Linear regression analysis was performed between the pre-perturbation isometric moment (independent) and the resultant peak imposed eccentric moment (dependent) for each subject (10 repetitions) and for each of the groups. Each individual subject demonstrated a strong linear relationship between the normalized magnitudes of the peak imposed eccentric moments and the magnitudes of the pre-perturbation isometric moments (see r values in Table 3). The following linear relationships were observed between the normalized magnitudes of the peak imposed eccentric moments and the magnitudes of the pre-perturbation isometric moments for each group:

Equation 1	NWT	$\mathbf{y = 1.45\,x + 7.01,\ r = 0.99}$
Equation 2	WT	$\mathbf{y = 1.42\,x + 5.90,\ r = 0.99}$
Equation 3	Both Groups	$\mathbf{y = 1.44\,x + 6.26,\ r = 0.99}$

Table 3. Individual step test results. The minimum and maximum pre-perturbation isometric values are shown (Min % MVC and Max % MVC).

Subject	Intercept	Slope	r	Min %MVC	Max %MVC
NWT					
1	5.63	1.50	0.999	9.7	63.0
2	7.88	1.41	0.994	12.4	64.5
3	9.27	1.41	0.998	16.7	94.2
4	7.69	1.42	0.991	12.7	70.1
5	8.71	1.44	0.993	6.6	83.3
6	8.41	1.43	0.999	5.4	67.7
7	9.27	1.36	0.994	6.6	93.8
8	5.22	1.47	0.997	6.6	72.0
9	7.19	1.37	0.997	6.6	86.2
10	3.64	1.52	0.993	6.1	75.8
11	-1.16	1.74	0.996	7.2	72.9
12	7.02	1.47	0.996	3.0	72.9
13	5.77	1.54	0.996	3.2	66.6
14	6.05	1.39	0.999	8.1	89.7
15	5.81	1.49	0.986	8.1	74.6
WT					
1	5.66	1.46	0.996	3.9	65.4
2	3.38	1.44	0.998	2.9	59.3
3	6.93	1.28	0.998	8.2	83.1
4	4.88	1.55	0.997	6.2	69.1
5	3.54	1.40	0.990	7.6	57.3
6	5.12	1.41	0.993	7.6	70.9
7	-0.21	1.56	0.995	6.9	67.5
8	5.24	1.48	0.998	6.5	71.9
9	8.26	1.37	0.992	6.5	62.9
10	8.94	1.40	0.998	6.3	75.2
11	9.34	1.38	0.995	6.3	70.2
12	3.85	1.44	0.997	6.2	70.1
13	5.78	1.42	0.996	9.2	85.1
14	7.43	1.37	0.997	4.6	85.1
15	9.25	1.40	0.999	2.9	70.0

No significant differences were noted between the NWT and WT groups for intercept or slope of the linear regression equations (two-tailed, independent t tests). The minimum and maximum pre-perturbation isometric moment levels were also not significantly different between the groups. The peak imposed eccentric moments occurred at 69.3° ± 1.3 SD for the WT group and at 69.2° ± 1.1 SD for the NWT group.

Because the groups did not demonstrate any significant differences in terms of intercept, slope or angle of occurrence of peak imposed moment, the linear regression equation for both groups combined (n = 30) was used to predict the maximum imposed eccentric moment (y) corresponding to 100% MVC (x = 100). The predicted maximum imposed eccentric moment was equal to 150.3 % MVC for the WT and NWT groups combined (Figure 3). As is evident in Figure 3, very little extrapolation from gathered data

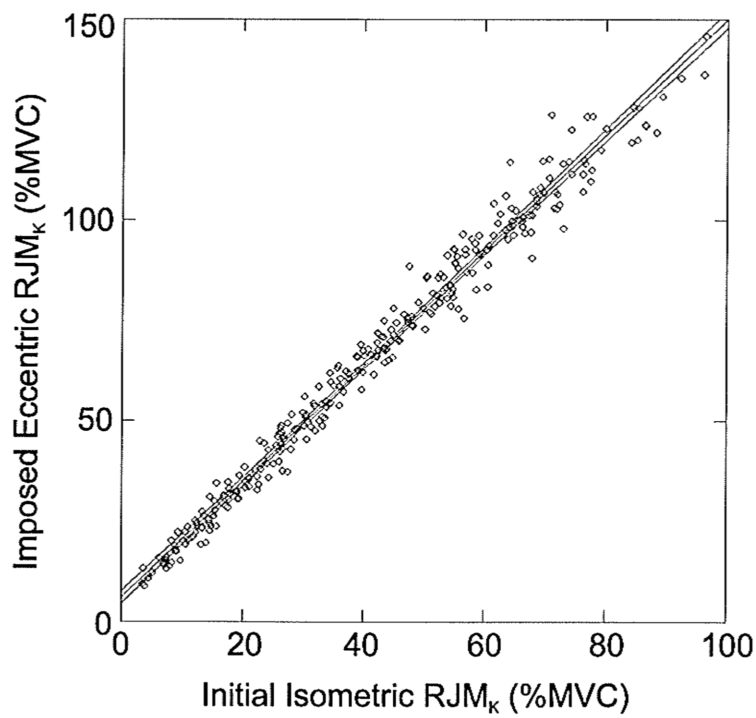

Figure 3. Relationship between the peak imposed eccentric moments and the pre-perturbation isometric moments from the step test. A strong linear relationship was observed (y = 1.44x + 6.26, r = 0.99, 99% confidence interval). For each subject (n=30), ten pre-perturbation isometric contractions were performed (range 2.9 to 94.2 %MVC for the group).

points was required to ascertain the predicted maximum imposed eccentric moment corresponding to 100% MVC.

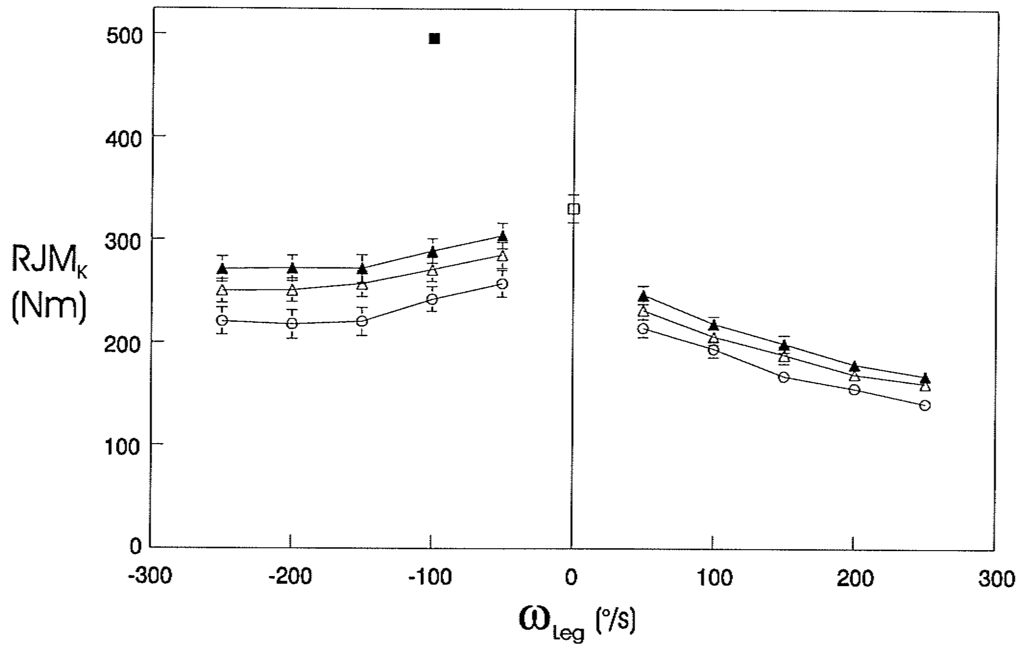

Figure 4. Resultant joint moment/angular velocity relationship for the knee extensors (n = 30) is plotted using the absolute peak moments (▲), mean peak moments (Δ), and mean angle-specific moments at 70° (o). The mean MVC (□) and the maximum imposed eccentric moment (■) predicted from the linear equation obtained from the step test (Figure 3) are also shown. Standard error bars are illustrated when they exceed the symbol size. Positive velocity corresponds to concentric knee extensor contraction and negative velocity corresponds to eccentric knee extensor contraction.

The RJM$_K$/angular velocity relationship is shown in Figure 4. The absolute peak moments (peak moment with the greatest magnitude recorded during the 3 repetitions), mean peak moments (average peak moment of 3 repetitions) and angle-specific moments (average moment recorded at 70° over 3 repetitions) are plotted for both groups combined (n = 30). The predicted maximum imposed eccentric moment (150% MVC or 495.8 Nm) was substantially greater than MVC (330.55 Nm ± 13.54 SE) measured at the same joint angle (70°). At the same angular velocity (-100°/s), the predicted maximum imposed eccentric moment was 183% of the mean peak eccentric moment (271.03 Nm ± 10.99 SE), 172% of the absolute peak eccentric moment (289.1 Nm ± 12.25 SE) and 204% of the angle-specific eccentric moment (242.49 Nm ± 11.09 SE).

The relative degree of neural regulation present during voluntary eccentric contractions was quantified by comparing the predicted maximum imposed eccentric moment (determined by the step test) to the angle-specific moment recorded during the isovelocity strength test. The imposed eccentric moments and the angle-specific moments were measured at the same velocity (-100°/s) and at the same joint angle (70°). Two-tailed paired *t test* analysis revealed that predicted maximum imposed eccentric moments were significantly greater than voluntary eccentric angle-specific moments for both groups ($p < 0.001$). The differences between the predicted maximum imposed eccentric moments and the angle-specific moments were subjected to two-tailed independent *t* test analysis to determine whether differences existed in the relative degree of neural regulation between the NWT and WT groups. No significant difference was found.

Strength Tests

MVC

Subjects in the WT group produced greater knee extensor and knee flexor isometric moments (MVC normalized to body mass) as compared to the NWT group (one-tailed, independent *t* tests, $p<0.05$ and $p<0.01$ respectively). Normalized MVC values are represented for each group along with their respective SE bars in Figure 5. The absolute values of the MVC tests are outlined in Table 4.

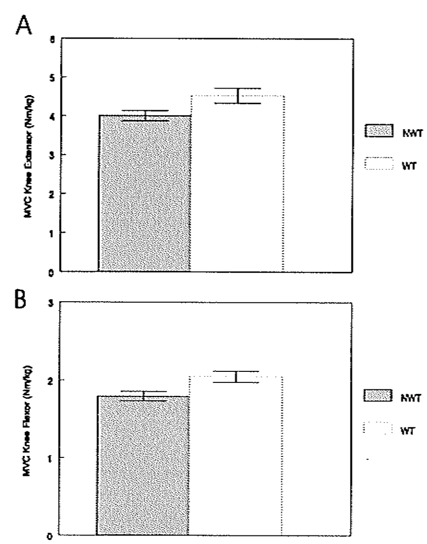

Figure 5. Knee extensor and knee flexor MVC values normalized to body mass. SE bars are shown.

Table 4. Absolute resultant joint moment values for MVC tests.

		MVC (Nm)
NWT		
	extensor	**308.53 ± 15.09 SE**
	flexor	**137.95 ± 5.75 SE**
WT		
	extensor	**361.39 ± 19.92 SE**
	flexor	**162.71 ± 6.61 SE**

Isovelocity Strength Tests

The RJM_k/angular velocity relationship for knee extension and knee flexion for the NWT and WT groups are illustrated in Figure 6. Mean peak moments and absolute peak moments have been normalized to body mass (Nm/kg) and are plotted with standard error bars at each testing velocity. Concentric velocities are designated as positive and eccentric velocities are designated as negative.

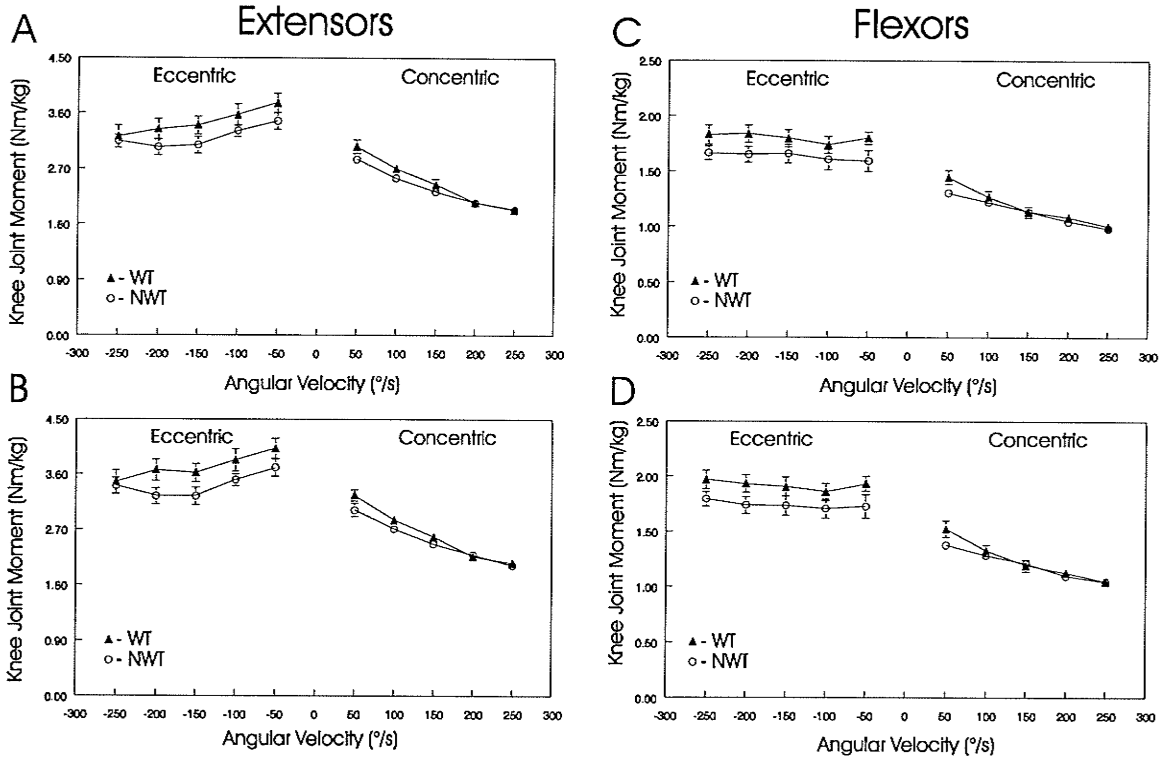

Figure 6. Body mass normalized RJM$_k$/angular velocity relationships for mean peak moments (top panel) and absolute peak moments (bottom panel). Relationships for the knee extensors are plotted on the left and those for the knee flexors are plotted on the right. Solid triangles - WT group. Open circles - NWT group. SE bars are shown.

The statistical analysis of the knee extensor eccentric mean moment data is displayed in the ANOVA table in Table 5. This ANOVA format was used in the analysis of mean peak moment, absolute peak moment, angle-specific moment and angle of occurrence of peak moment for knee extensor and knee flexor concentric and eccentric contractions. Because graphical interpretation of the RJM$_k$/angular velocity relationships for the knee musculature demonstrated that the relationship between moment generation with velocity of testing was very similar between the NWT and WT groups, groups were combined to test for velocity effect on moment generation.

Table 5. Example ANOVA table summarizing results for knee extensor eccentric mean peak moment (Nm/kg).

Source of Variation	SS	DF	MS	F-ratio	P
Group	2.325	1	2.325	7.580	0.007
Velocity	4.322	4	1.080	3.522	0.009
Error	44.168	144	0.307		

Analysis of knee extensor eccentric mean peak moment results demonstrated statistically significant differences between groups (p = 0.007) and between velocities (p = 0.009). As illustrated in Figure 6, the WT group generated greater mean peak moments as compared to the NWT group and mean peak moments generally decreased with increasing velocity of testing. Similar group and velocity differences were also observed for knee extensor concentric mean peak moments, knee extensor eccentric absolute peak moments and knee extensor concentric absolute peak moments. Analysis of knee flexor eccentric mean peak moment and absolute peak moment revealed significant group differences (WT generated greater moments than NWT) but no velocity effect (eccentric moments flat with increasing velocity of testing). Knee flexor concentric mean peak moment and absolute peak moment analysis did not show any differences between the groups, however, a velocity effect was observed (moments decreased with increasing velocity of testing). P-values of ANOVA results are listed in Table 6.

Table 6. P-values of ANOVA results. Mean (peak) moment, best moment (absolute peak moment), angle (specific) moment and angle (of occurrence) of peak moment analyses are included. Significant values ($p<0.05$) are italicized.

		Eccentric		Concentric	
		Group	**Velocity**	**Group**	**Velocity**
Extensor	**Mean Moment**	*0.007*	*0.009*	*0.049*	*0.001*
	Best Moment	*0.002*	*0.017*	*0.035*	*0.001*
	Angle Moment	*0.001*	*0.013*	0.261	*0.001*
	Angle of Peak	*0.002*	*0.001*	0.485	*0.001*
Flexor	**Mean Moment**	*0.001*	0.967	0.094	*0.001*
	Best Moment	*0.001*	0.377	0.182	*0.001*
	Angle Moment	0.057	0.767	0.411	*0.001*
	Angle of Peak	0.061	0.758	0.268	*0.001*

The body mass normalized RJM_k/angular velocity relationship for knee extension and knee flexion for angle-specific moment is illustrated in Figure 7. Knee extensor angle-specific moments were recorded at 70° and knee flexor angle-specific moments were recorded at 25°. Concentric velocities were designated as positive and eccentric velocities were designated as negative. The angle of occurrence of peak moment was also determined for each velocity of testing and plotted with standard error bars. As is illustrated in Figure 7, knee extensor eccentric angle-specific moments were greater in the WT subjects and decreased with increasing velocity of testing. The angle of knee extensor eccentric peak moment occurrence differed between the groups. WT subjects generated peak moments relatively further into the range of motion compared to the NWT subjects. A velocity effect was also observed in that peak eccentric knee extensor moments were generated earlier in the range of motion with increasing velocity of testing. No differences were observed between the groups for knee extensor concentric angle-specific moment and angle of peak moment occurrence parameters. However, as is depicted in Figure 7, knee extensor and knee flexor concentric angle-specific moments decreased with increasing speed of testing. Concentric peak moments occurred earlier in the range of motion with increasing velocity of testing (i.e. closer to horizontal for concentric knee extension and in greater degree of flexion for concentric knee flexion). No statistically significant differences were not found between groups for knee flexor eccentric angle-specific moment or angle of peak moment occurrence. However, the p values for these tests ($p = 0.057$ and $p = 0.061$ respectively) suggest that the power of this study may have been too low to show these differences. Eccentric knee flexor angle-specific moments and angles of peak moment occurrence did not change with increasing velocity of testing. Concentric angle-specific moment and angle of peak moment occurrence were not different between the WT and NWT groups for knee flexion.

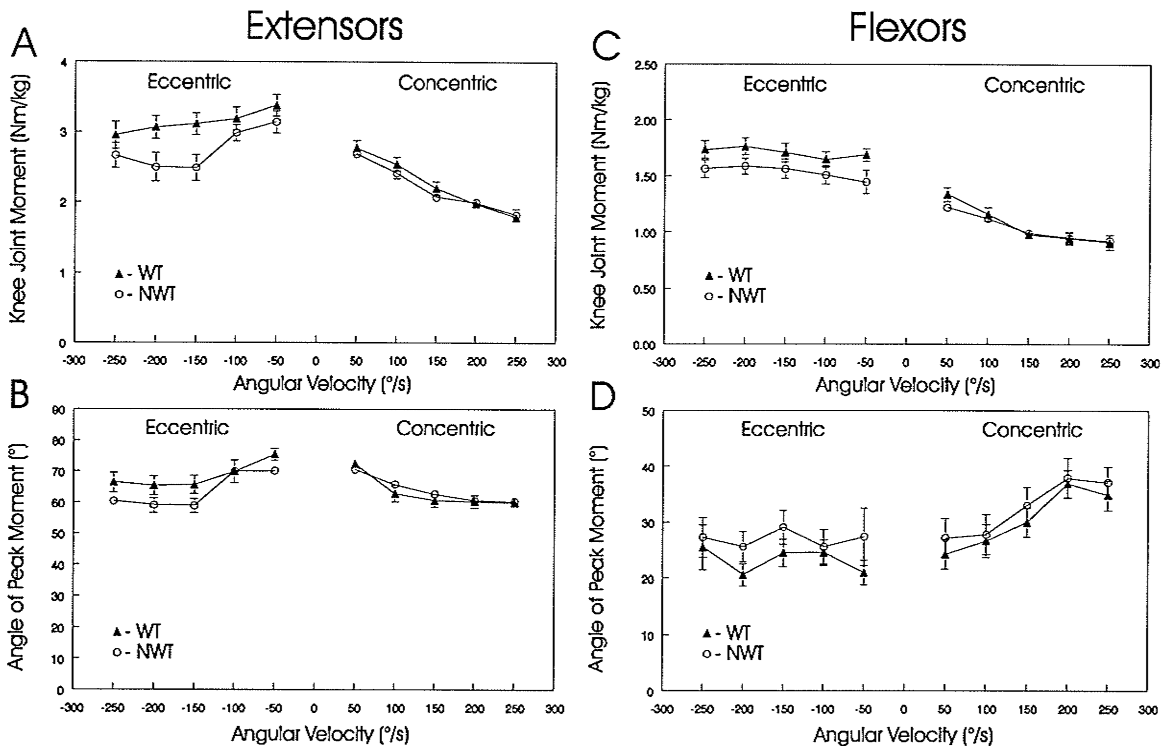

Figure 7. Body mass normalized RJM_k/angular velocity relationships for angle-specific moments (top panel, knee extension at 70° and knee flexion at 25°) and angle of occurrence of peak moment (bottom panel). Relationships for the knee extensors are plotted on the left and those for the knee flexors are plotted on the right. Solid triangles - WT group. Open circles - NWT group.

Non-normalized knee extensor and knee flexor RJM_k/angular velocity values (and standard error values) for mean peak moment (mean moment), absolute peak moment (best moment), angle-specific moment (angspec) and angle of peak moment occurrence (angpeak) are presented in table form in Appendix E.

Strength Maps

Knee extensor and knee flexor strength maps were generated for each subject and then normalized to body mass. Individual strength maps were averaged to produce average knee extensor strength maps for the NWT and WT groups (Figure 8). Average knee flexor strength maps were also generated for the NWT and WT groups (Figure 9). Difference maps were generated by subtracting the average NWT strength maps from the average WT strength map for both knee extension and knee flexion (included in Figure 8 and Figure 9 respectively). Confidence maps were also generated to provide information about whether the group differences demonstrated by the difference map were statistically significant.

The knee extensor difference map demonstrated an angle and velocity matched peak moment difference of 0.83 Nm/kg (approximately 65 Nm). Regional analysis was performed using a threshold value of 0.2 Nm/kg (approximately 15.6 Nm). The NWT group demonstrated a knee extensor strength deficit over 13.8 % area of the map when this threshold value was used. This deficit was largely localized to the quadrant depicting eccentric moment generation over the inner range of motion (angles of 60 to 95° knee flexion, velocities of -250°/s to 26°/s). Using an F value of 2.40 and an alpha level of 0.05, 14.7 % of the knee extensor strength map was found to be significantly different between the 2 groups (similar to the difference map). This area of significant difference was located between 49 and 95° range of motion and over the velocities of -250°/s to 56°/s.

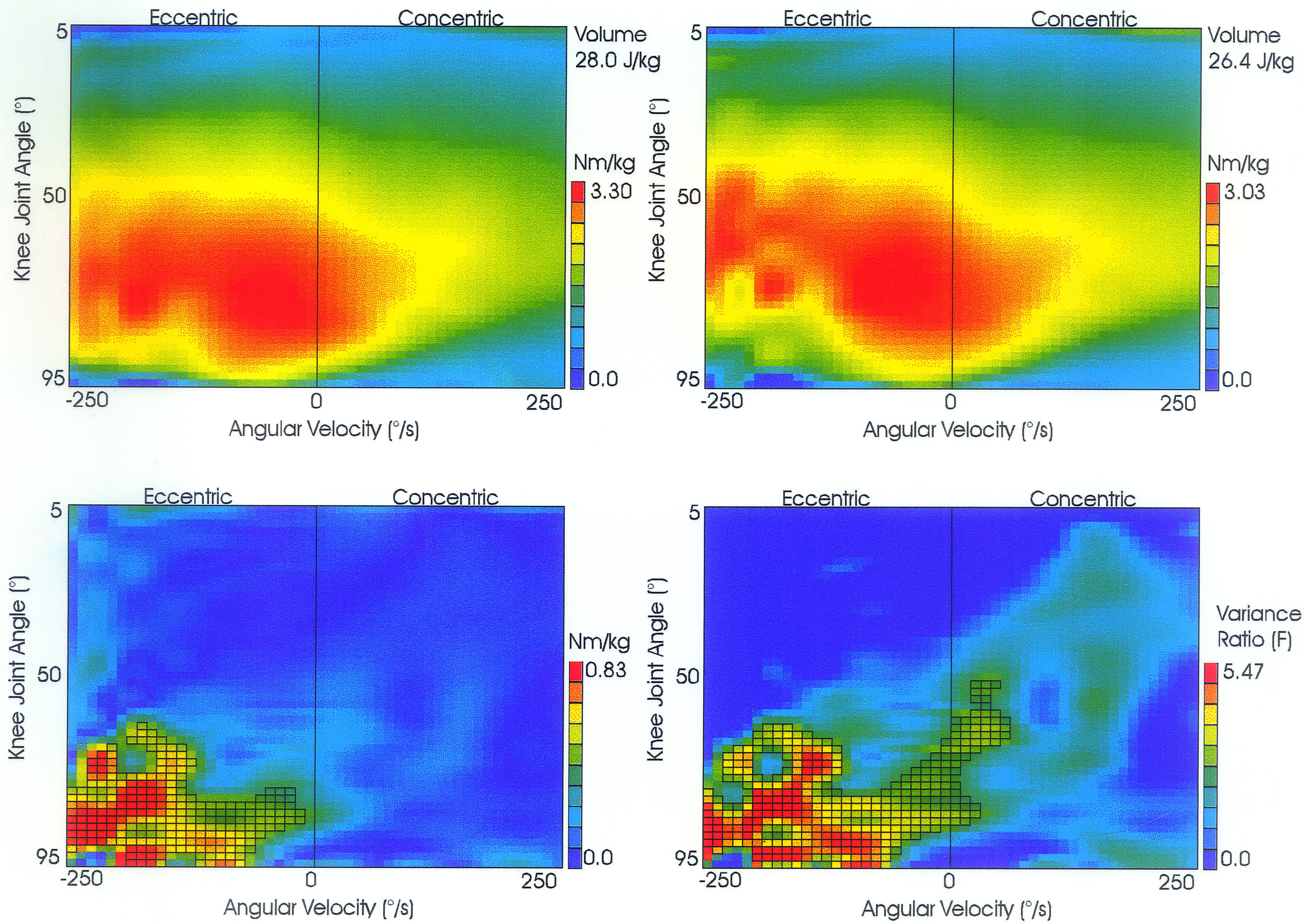

Figure 8. The body mass normalized average knee extensor strength maps are shown for the WT group (top left) and the NWT group (top right). The knee extensor difference map (bottom left) is derived by subtracting the average knee extensor NWT strength map from the average knee extensor WT strength map. The knee extensor confidence map (bottom right) depicts the F ratio (variance of WT divided by variance of NWT) over the tested domain (map area). For all maps, the leg angular velocity is shown on the horizontal axes and the knee joint angle is shown on the vertical axes. The color-coded scale bar is calibrated in Nm/kg for the strength maps and difference map. The scale bar on the confidence map is the F ratio. The areas highlighted by the overlay grid for the difference and confidence maps corresponds to regions detected using threshold values (see text for details).

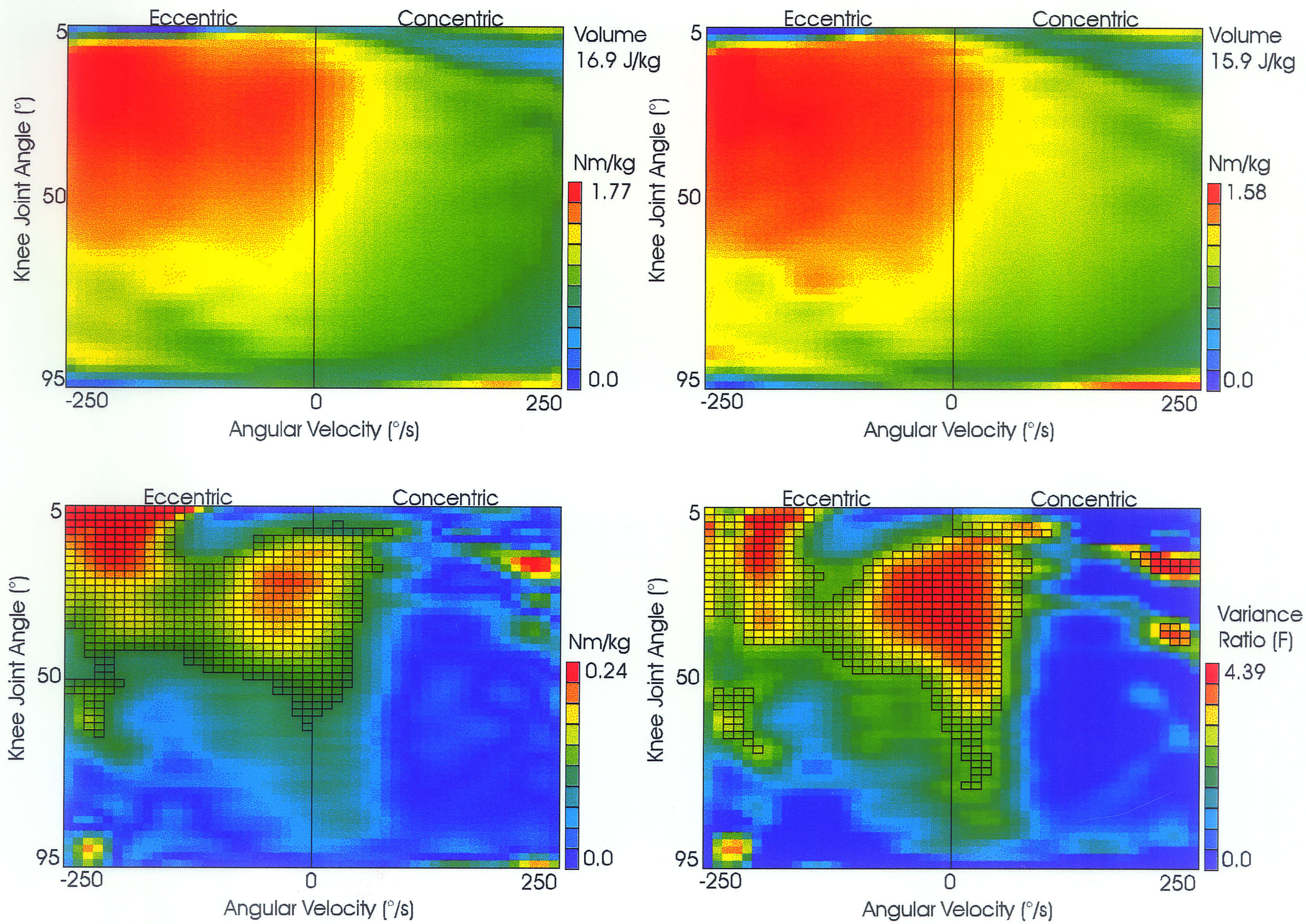

Figure 9. The body mass normalized average knee flexor strength maps are shown for the WT group (top left) and the NWT group (top right). The knee flexor difference map (bottom left) is derived by subtracting the average knee flexor NWT strength map from the average knee flexor WT strength map. The knee flexor confidence map (bottom right) depicts the F ratio (variance of WT divided by variance of NWT) over the tested domain (map area). For all maps, the leg angular velocity is shown on the horizontal axes and the knee joint angle is shown on the vertical axes. The color-coded scale bar is calibrated in Nm/kg for the strength maps and difference map. The scale bar on the confidence map is the F ratio. The areas highlighted by the overlay grid for the difference and confidence maps corresponds to regions detected using threshold values (see text for details).

Analysis of the body mass normalized knee flexor difference map revealed an angle and velocity matched peak moment difference of 0.24 Nm/kg (approximately 18.7 Nm).The difference between the WT and the NWT groups was greater than or equal to 0.1 Nm/kg (approximately 7.8 Nm) over 24.9 % of the map area. This region of difference was located between 5 to 62° range of motion and over the velocities ranging from -250°/s to 77°/s. The confidence map (F-ratio map) generated for the WT and NWT average knee flexor maps revealed an area of 25.2 % difference between the two group maps (F value >2.4 and alpha 0.05). The requirements used for determining significant difference in generating the knee extensor confidence map were also followed in generating the knee flexor confidence map (minimum of 6 neighbor squares and a minimum area of 6 squares). The largest area of significant difference (23.5% of the 25.2% area difference) was located between 5° and 75° range of motion over the velocities of -250°/s to 97°/s.

The average knee extensor and knee flexor strength maps plotted in Figure 8 and Figure 9 showed obvious differences in terms of magnitude of moments achieved, shape of the map surface and quadrant of peak moment occurrence. As is evident from the data presented, isometric, eccentric and concentric knee extensor moments were greater than their respective knee flexor moments (note that the strength map color coding is scaled to the maximum body mass normalized moment). Visual analysis demonstrated that peak knee extensor moments were located in the bottom left quadrant of the strength map (eccentric contractions, 49-95° range of motion), whereas peak knee flexor moments were located in the top left quadrant of the map (eccentric contractions, 5-75° range of motion). Interestingly, peak moments occurred over virtually the same range of velocities for isovelocity tests of knee extension (-250°/s to 77°/s) and for knee flexion (-250°/s to 97°/s).

In both the NWT and WT groups, the slopes of the concentric moment drop-off with increasing velocity of testing was greater for the knee extensors compared to the knee flexors (Figure 6). For the NWT group, concentric extensor slope was equal to -0.0041 and concentric flexor slope was equal to -0.0016. Two-tailed paired t test analysis revealed a significant difference ($p < 0.05$). For the WT group, concentric extensor slope was equal to -

0.0052 and concentric flexor slope was equal to -0.0021. Paired *t* test analysis on this data also revealed a significant difference ($p<0.05$).

Analyses of the slopes of the concentric mean peak moment/angular velocity relationships for knee extension and knee flexion (Figure 6) revealed no significant differences between the WT and NWT groups. For both knee extension and knee flexion, the slope of the concentric moment decrement tended to be larger in the WT group, but this difference was not statistically significant (independent, two-tailed *t* tests).

As is evident on visual inspection of the RJM_k/angular velocity plots (Figure 6), the ANOVA results table (Table 7), and the strength difference/confidence maps, NWT and WT strength differences were most apparent eccentrically. Relative to their concentric strength levels, the WT group demonstrated greater eccentric moments than the NWT group.

Knee flexor:extensor ratio maps were generated for both the NWT and WT groups. The WT knee flexor:extensor ratio map is shown in Figure 10. Contraction-type, velocity and angle of joint range of motion were matched between flexor and extensor maps. No significant differences were noted in the shape of the ratio maps or in the magnitudes of ratios between NWT and WT groups. Ratio values varied from 1.64 (knee flexor moments = 1.64X knee extensor moments) in the upper left quadrant of the strength ratio map to 0.36 between 55-70° of knee flexion across all velocities concentrically and eccentrically. The knee flexors were the most strong relative to the knee extensors on the eccentric side of the ratio map over all speeds of testing with the range of motion near full extension. The range of ratio values portrayed on this map (0.18 - 1.64) clearly demonstrate that the relationship between maximum knee flexor and knee extensor strength is highly dependent on the contraction type, velocity and joint position.

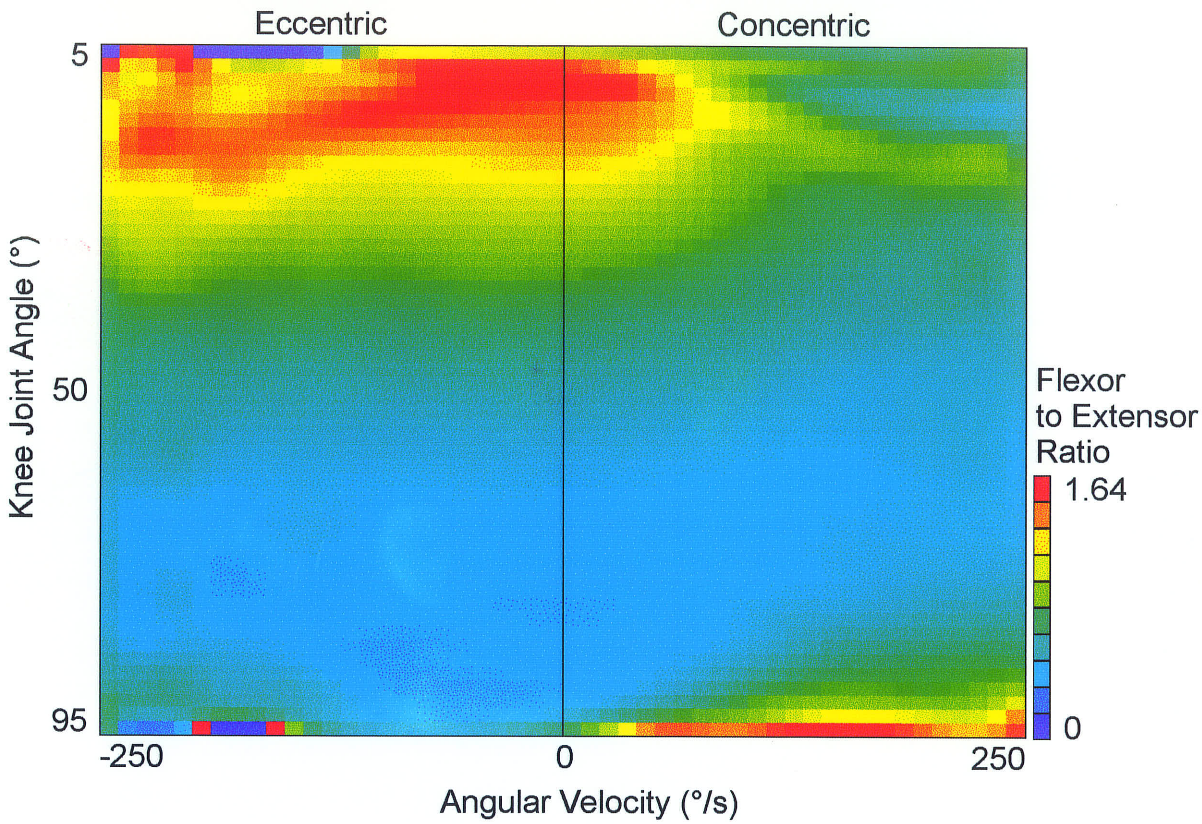

Figure 10. The average knee flexor:extensor ratio map is shown for the WT group. This ratio map is produced by division of the average WT knee flexor strength map by the average WT knee extensor strength map. As such, the knee flexor:knee extensor ratios are angle and velocity matched. A similar pattern and range of ratio magnitudes was observed for the average ratio map of the NWT group.

The mean volumes (J/kg) were determined for the average knee extension and average knee flexion maps for both groups (volume under the body mass normalized moment/angle/angular velocity plots). Map volumes are depicted in Figure 11. The mean volume (J/kg ± SE) of the average knee extensor strength map for the NWT group was 26.30 J/kg ± 0.70. The mean volume of the average knee extensor strength map for the WT group was 27.83 J/kg ± 0.91. No significant difference was detected between the groups (one-tailed, independent t test). The mean volume of the average knee flexor strength map for the NWT group was 15.82 J/kg ± 0.49. The mean volume of the average knee flexor strength map for the WT group was 16.80 J/kg ± 0.60. Statistical analysis revealed no significant difference between the groups.

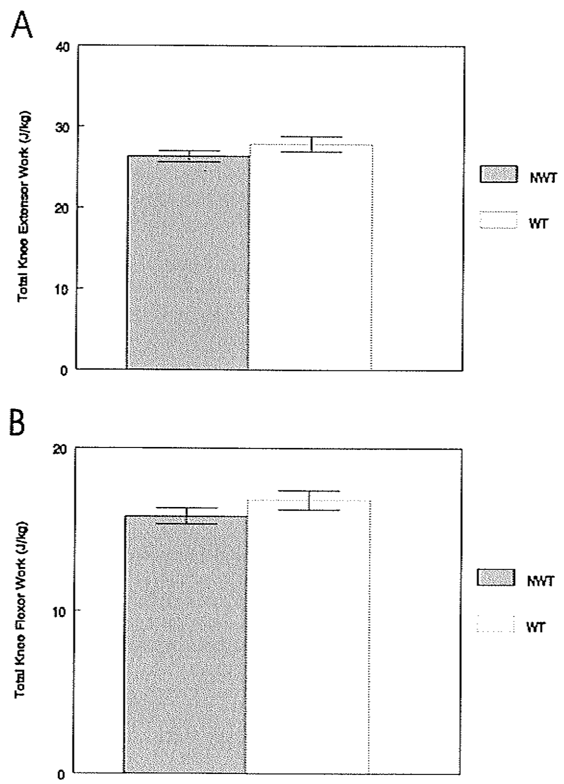

Figure 11. Volume of body mass normalized knee extensor (top panel) and knee flexor (bottom panel) RJM_k/angle/angular velocity strength maps.

Discussion

Step Test

Moment/angle/angular velocity relationships generated by the musculature about the knee were examined in NWT and WT individuals in this investigation. As well, voluntary and involuntary (imposed contractions) eccentric moment generation was studied. The relationship between neuromuscular activation level and resultant eccentric moment magnitude was determined in vivo. As hypothesized, results of this study indicate that an elastic component contributes to eccentric moment generation and that the expression of this elastic component is dependent on (and linearly related to) the degree of actomyosin engagement in muscle. These results suggest that this elastic component is resident in the muscle sarcomere (actin, myosin, titin, Z-disc). Imposed eccentric moments approached magnitudes relative to MVC comparable to in vitro force/velocity data. However, previous in vivo strength studies have not reported eccentric moments of this magnitude and a neural regulatory mechanism is believed to exist which limits voluntary eccentric moment generation. Contrary to what was hypothesized, the relative difference between the predicted eccentric moments and the maximal effort eccentric moments were not significantly different between the groups. However, WT males demonstrated significantly greater strength of the knee extensors and flexors when tested isometrically and eccentrically consistent with a difference in neural activation patterns. Concentric strength differences were restricted to low velocities for the knee extensors and were not different for the knee flexors. Analysis of total work performed during the isovelocity strength tests (volume of moment/angle/angular velocity plot) revealed no significant differences between the WT and NWT groups.

Some of the neuromuscular factors which contribute to eccentric moment generation were examined in this study. Data from each subject demonstrated that a strong linear relationship existed between the pre-perturbation isometric moment and the resultant imposed eccentric moment. Therefore, the magnitude of the resultant eccentric moment was related to the level of the pre-perturbation isometric contraction which corresponded to a specific degree of muscle activation or amount of actomyosin engagement. This relationship has been demonstrated previously in vitro (Blange et al. 1972, Flitney and Hirst 1978). The enhanced force production observed during eccentric contractions has been attributed to an elastic component resident within the activated sarcomeres of muscle. Z-discs, titin, myosin and actin all represent potential sources of this actomyosin dependent elasticity (Blange et al. 1972, Horowits 1992, Huxley and Simmons 1971, Trombitas and Pollack 1993). The additional force contribution of this elastic component in muscle permits eccentric moment generation which substantially exceeds isometric and concentric values when neural control mechanisms are not active (i.e. in maximally stimulated, isolated muscle preparations). This elastic mechanism of enhanced eccentric force production is consistent with observations that oxygen uptake is substantially lower during eccentric activity when compared to concentric activity (Abbott et al. 1952, Bonde-Petersen et al. 1972, Knuttgen et al. 1971). As well, electromyographic activity of the knee extensors has been shown to be lower during maximum voluntary eccentric contractions as compared to concentric contractions (Moritani et al. 1988, Seger and Thorstensson 1994, Westing et al. 1991) which is consistent with an elastic contribution to eccentric moment generation. As hypothesized, the linear relationship between the degree of muscle activation during the pre-perturbation isometric moment and the resultant imposed eccentric moment was not significantly different for WT and NWT subjects. This finding also supports the theory that physiological elastic properties at the level of the muscle sarcomere and not increased activation levels are primarily responsible for the enhanced force production seen in eccentric contractions when neural influences are removed.

The in vivo moment/angular velocity relationship does not resemble the shape of the in vitro force/velocity relationship. This can be explained by the fact that voluntary generation of moment involves the complex interaction of multiple neural, mechanical and muscular factors to produce RJM in humans. However, if muscles were fully activated during isovelocity strength tests, one would expect that the eccentric to isometric moment ratio would be consistent in magnitude with that observed in isolated muscle. Previous studies have been unable to demonstrate eccentric to isometric moment ratios comparable to in vitro data (Dudley et al. 1990, Mayer et al. 1994, Westing et al. 1991, Westing and Seger 1989, Westing et al. 1988, Westing et al. 1990). In this study, a new method called the step test was used to predict the maximum imposed eccentric moment. This maximum imposed eccentric moment was found to be 150% MVC, consistent with in vitro force/velocity data (Edman et al. 1978, Harry et al. 1990, Haugen 1991, Lombardi and Piazzesi 1990). This finding reinforces the notion that neural influences are primarily responsible for the differences demonstrated between the eccentric portions of the force/velocity and moment/angular velocity relationships.

The velocity of muscle lengthening has been shown to influence the magnitude of increase in force elicited with stretch in isolated muscle preparations (Edman et al. 1978, Flitney and Hirst 1978). In this investigation, the step test was performed at two additional velocities on one subject. As predicted from in vitro force/velocity data, the maximum imposed eccentric moments were observed to increase in a linear fashion with increasing velocity of testing, reaching 167% MVC at 150°/s and 183% MVC at 200°/s. These findings are well within the range observed for in vitro muscle studies.

In comparison to other studies which have applied stretch to voluntarily activated muscle (Gulch et al. 1991, Thomson and Chapman 1988), the findings of this study revealed substantially greater imposed eccentric moments. Although Gulch and colleagues demonstrated that forced lengthening of activated muscle induced a double-peaked increment in force, they did not interpret or quantify this phenomenon. Data from the study by Thomson and Chapman (1988) indicated that the peak imposed eccentric forearm supination moments ranged from approximately 108-126% of maximum isometric moment. However, Thomson and Chapman used the peak eccentric moment generated at the end of a large imposed range of motion (large and long duration stretch) to represent imposed eccentric moment. Given the large ranges of motion (80° and 160°) and the total time associated with this motion, voluntary and involuntary neural control mechanisms may have influenced the magnitudes of these moments. Westing and colleagues (1990) demonstrated that angle-specific eccentric moments increased by only 21-24% above MVC when electrical stimulation was superimposed during maximum voluntary eccentric contraction.

In comparison to the results of this study, this relatively small increase may be explained by the fact that the tolerated level of transcutaneous electrical stimulation likely did not allow activation of all the nerves supplying the muscle fibres.

Investigators have speculated that a neural regulatory mechanism may limit the level of muscular activation during voluntary eccentric contractions to protect the musculoskeletal system from injury (Hortobagyi and Katch 1990, Westing et al. 1991, Westing et al. 1988). Westing and colleagues (1991) demonstrated that quadriceps EMG levels were lower for maximal effort eccentric contractions compared to concentric contractions at identical velocities which is consistent with the notion that full neuromuscular activation does not occur during voluntary eccentric activity. In our study, by assuming that RJM_k primarily reflects knee extensor activity, the level of knee extensor activation required to generate the observed maximal voluntary eccentric moments would correspond to only 55.6% MVC as predicted by the step test linear equation (using the mean peak moment for both groups combined at -100°/s for comparison). In order to further quantify the restriction of neuromuscular activation during voluntary eccentric contractions, the predicted maximum imposed eccentric moment derived from the step test was compared with the angle-specific eccentric moment measured during the strength test to reveal that the imposed (involuntary) eccentric moments were double the voluntary eccentric moments (204% angle-specific moment for both groups combined). To control for muscle length and velocity dependent factors, the comparison was made at the same joint angle (70°) and for the same angular velocity (-100°/s). These differences represent a substantial decrement in moment generating capacity which can be explained by the existence of a potent neural regulatory mechanism which limits motor unit activation (recruitment of motor units and/or limits discharge frequency of motor units) during voluntary eccentric contraction. Any stretch evoked activation of the quadriceps would contribute minimally (less than 10 Nm, unpublished data) to the imposed eccentric moment and would be inconsequential as the step test velocity was below the threshold for stretch reflex activation (Burke et al. 1970, von Kampen 1996).

The RJM_k measured during the step test arose from flexor and extensor muscle forces which both act to influence segmental rotation about the knee. Co-contraction of the knee extensors and flexors in known to occur during isovelocity strength tests (Snow et al. 1993). Increased knee flexor activity would result in a decrease in extensor moment magnitude. However, it is difficult to envision that increased knee flexor activity during voluntary knee extensor eccentric contractions could solely account for the substantial difference observed between the imposed and the voluntary eccentric moments. Further study of the electromyographical activity patterns of knee flexors and extensors is required to rule out this possibility.

Contrary to what was hypothesized, quantification of the relative degree of neural regulation present during voluntary eccentric contractions (angle-specific eccentric moment measured during the strength test was subtracted from the predicted maximum imposed eccentric moment derived from the step test) revealed no significant differences between the NWT and WT groups. Regular resistance training as performed by the WT subjects in this study may not have altered the neural control of eccentric contractions to the extent that differences in the <u>relative</u> levels of neural regulation could be detected during constant velocity eccentric testing at 100°/s. Other types of training or other types of experimental procedures or conditions may demonstrate differences in the degree of neural regulation.

The extent to which this neural regulation occurs in other behaviours, such as locomotion, remains to be examined. It is quite possible that this neural regulatory mechanism may be modified by specific training programs or by medical conditions which cause changes in the pre-motoneuronal interneuronal circuitry and/or the motoneuronal excitability. For instance, the existence of pain or nocioceptive activity could alter the neural recruitment and neuromuscular activation patterns. This neural regulatory mechanism may be implicated in injuries which occur during deceleration when muscles generate high magnitude eccentric moments to slow the body's segments. For example, in throwing, the shoulder external rotator muscles act eccentrically after release of the ball to slow the upper arm segment and maintain glenohumeral joint stability. Changes in the selective neural recruitment or activation patterns could diminish the eccentric moment generation capacity of this musculature resulting in decreased ability to control the motion and increasing the likelihood of injury. Certainly, this study reveals that the motoneuron excitability (as reflected by the ability to generate eccentric moments) is substantially limited by an unknown neural mechanism during eccentric contraction. This finding may reflect that the recruitment and discharge of motor units during eccentric muscle contractions may be more labile than during concentric contractions. Thus eccentric activity patterns may be more susceptible to effects of pain or nocioception. Further study of the influence of injury on eccentric and concentric muscle contraction is warranted.

During human motion, a neural regulatory mechanism may control excursions into a "reserve" region demarcated by the maximum voluntary eccentric moments (lower bound) and by the maximum predicted imposed eccentric moments (upper bound) to limit damage to muscle, tendon and bone. The conditions under which excursions into this reserve region are allowed are unknown. During certain behaviours such as landing from a leap, running downhill, or with corrective or catastrophic responses (i.e. eccentric activity required during follow-through after missing the ball in a racquet sport), generation of eccentric moments in this reserve region may occur. Although the occurrence of muscle injury after moderate to high level eccentric exercise is well documented, the relationship between the degree of injury and eccentric moment generation in the reserve region is unknown. Certainly, the degree of muscle damage will be related to a number of factors such as strain magnitude, strain rate, and strain duration, and state of muscle fatigue (Lieber et al. 1991). In this study, brief (<200 ms) eccentric contractions were produced during the step test corresponding to RJM_k values in the upper half of the reserve region without overt muscle damage or reports of any delayed onset muscle soreness. This is consistent with a multi-factorial origin of muscle damage and delayed onset muscle soreness associated with eccentric exercise.

The MVC test was performed at 70° knee flexion to correspond to the angle of peak imposed eccentric moment during the step test (Figure 1). Maximum voluntary knee extensor isometric moments have also been shown to occur near this joint angle (Westing et al. 1989, Westing et al. 1988). Isometric moments recorded during this study were significantly greater than the maximum voluntary eccentric moments ($p<0.05$) which, in turn were greater than the concentric moments ($p<0.05$). Other studies have demonstrated that maximum eccentric moments generally vary within ± 15% of MVC (Dudley et al. 1990, Lacerte et al. 1992, Mayer et al. 1994, Westing and Seger 1989, Westing et al. 1988, Westing et al. 1990). The fact that MVC moments have been cited to be greater than maximum eccentric moments in some studies and less than maximum eccentric moments in other studies may relate to the fact that different definitions of MVC have been used for these comparisons. In some studies, MVC has been defined as the average moment recorded during the isometric contraction or as the average peak isometric moment recorded during different repetitions of isometric contractions (Dudley et al. 1990, Westing and Seger 1989, Westing et al. 1990). Other studies have used the absolute peak moment recorded during the isometric contraction(s) to represent MVC as was done in this study (Caldwell et al. 1993). Additional variability may exist depending on whether the isometric test is performed prior to or after the isovelocity tests in a strength evaluation. Another possibility is that the step test resulted musculotendinous microtrauma resulting in decreased force generating ability through direct disruption of sarcomeres or through nocioceptive inhibitory feedback to the motoneurons.

Strength Tests

As hypothesized, analysis of RJM_k/angle/angular velocity relationship data revealed that body mass normalized eccentric moments (mean peak moment and absolute peak moment parameters) were greater than concentric moments (for both the knee extensors and flexors) and that knee extensor moments exceeded knee flexor moments in both the WT and NWT groups. These findings are in agreement with the results of previous evaluations of knee strength (Alexander 1990, Caldwell et al. 1993, Griffin et al. 1993, Westing et al. 1988, Westing et al. 1990). The presence of actomyosin dependent elasticity in muscle and the use of different activation strategies for different types of contractions may allow for greater generation of moment during eccentric activity as compared to concentric activity. The magnitude of moments produced is also determined in part by the physiological cross-sectional area and the length of the moment arms of the involved muscle groups. Physiological cross-sectional area and moment arm differences between the quadriceps and hamstring muscle groups may be largely responsible for the different moment generation capabilities that exist for knee extension and flexion. The cross-sectional area of a muscle is proportional to the number of actomyosin cross-bridges arranged in parallel. Therefore, peak moments will be proportional to the number of fibres in cross-section. The cross-sectional area of the knee extensors has been shown to be greater than that of the knee flexors (An et al. 1981, Kanehisa et al. 1994). Wickiewicz et al. (1983) demonstrated that, based on architectural data, the quadriceps should theoretically be capable of producing twice as much force as the hamstring group. However, marked differences have been shown to exist between the quadriceps and hamstring muscle moment arm lengths as a function of joint angle (Herzog and Read 1993, Smidt 1973). Of course, neural, muscular and other mechanical factors also influence the generation of knee extensor and knee flexor moments.

As outlined in previous studies, concentric moments were shown to decrease with increasing velocity of testing and the slope of the moment decrement was less for the knee flexors than that exhibited for the knee extensors in both the NWT and WT groups (Caldwell et al. 1993, Colliander and Tesch 1989, Richards 1981, Wickiewica et al. 1984). Researchers have attempted to explain this variation in the slope of the concentric moment/angular velocity plot for the knee flexors and extensors in terms of the neural, mechanical and muscular properties that govern the generation of moment for these reciprocal muscle groups.

Caldwell and co-workers (1993) demonstrated that concentric peak moment decreased less with increasing velocity for the knee flexors (27% over 5 velocities spanning 50-250 °/s), producing a flatter moment/angular velocity relationship as compared to that of the knee extensors (which decreased 37%) in 8 NWT males (mean age 29 ± 4 years). Angle-specific moments measured at 60° below horizontal for the knee flexors and at 40° below horizontal for the knee extensors also decreased less with increasing velocity of concentric contraction for the knee flexors (17% decrease versus 24% decrease for the knee extensors). This finding has been demonstrated by other researchers (Colliander and Tesch 1989, Richards 1981, Wickiewica et al. 1984). In contrast, Prietto and Caiozzo (1989) found that angle-specific moments measured in 9 NWT male volunteers decreased less with increasing velocity from 0-240°/s for concentric tests of the knee extensors (approximately 40%) versus the knee flexors (approximately 48%). Some of the differences in the slope measurements noted in these two studies may be related to the fact that Prietto and Caiozzo included isometric contractions in their results and therefore tested over 6 velocities instead of the 5 concentric speeds assessed by Caldwell and co-workers. Similar to the study by Caldwell and colleagues, Prietto and Caiozzo measured angle-specific moments at 60° below horizontal for the knee flexors, however knee extensor moments were measured at 30° below horizontal. Prietto and Caiozzo speculated that the concentric extensor moment/angular velocity relationship would be flatter than that for the flexors because muscles with a greater proportion of fast twitch fibres are known to exhibit less force decrement with increasing velocity of contraction (and the quadriceps have been reported to be comprised of a greater percentage of fast-twitch fibres as compared to the hamstring muscle group - Johnson et al. 1973). However, the architectural design of the muscles within each muscle group may have greater bearing on the shape of the moment/angular velocity curve. Wickiewicz et al. (1984) stated that "the reduction in force potential of a muscle as a result of increasing velocities will be less in muscles having longer fibers (more sarcomeres in series)." It has been demonstrated that fibres of the knee flexors have a greater number of sarcomeres in series than fibres of the knee extensors which is consistent with the demonstration of flatter concentric moment/angular velocity plots for the knee flexors as compared to the extensors (Caldwell et al. 1993, Osternig 1986, Wickiewicz et al. 1984). It is evident from the existence of this controversy in the literature that the RJM and its relationship to velocity of testing can not be adequately explained by analysis of only one factor among the many factors responsible for dictating the shape of the moment/angular velocity relationship.

The slopes of the concentric sides of the moment/angular velocity plots were shown to be comparable for WT and NWT subjects. Similar findings were reported in previous knee strength studies involving subjects from different training backgrounds (Alexander 1990, Brown and Wilkinson 1983, and Taylor et al. 1991). In contrast to this finding, Hortobagyi and Katch (1991) reported that concentric elbow extensor and flexor moments remained constant in low strength subjects and increased with increasing velocity of testing in high strength subjects. However, the mean body mass for subjects in the low strength group was 14 kg less than the mean mass for subjects in the high strength group. Hortobagyi and Katch did not normalize moments to body mass which if used, may have resulted in the demonstration of different concentric strength relationships.

The magnitude of eccentric knee flexor moments (mean peak moment, angle-specific moment and absolute peak moment) remained relatively constant across all velocities of testing in this study. Similar eccentric moment/angular velocity relationships have been previously demonstrated for the knee flexors and extensors (Dudley et al. 1990, Griffin et al. 1993, Lacerte et al. 1992, Westing and Seger 1989, Westing et al. 1988, Westing et al. 1990). However, unlike previous results, eccentric knee extensor moments (mean peak moment, absolute peak moment and angle-specific moment) decreased with increasing velocity of testing in this study. The magnitude of decrease in mean peak and absolute peak moments from -50°/s to -250°/s was relatively small, equal to approximately 23 Nm in the NWT group and to 45 Nm in the WT group. Variations in protocols used in different studies likely explain this small discrepancy in the shape of the eccentric moment/angular velocity relationship.

Absolute and body mass normalized mean peak moments and absolute peak moments recorded in this study were found to be in agreement with previously reported data. Absolute values of the mean peak moments and absolute peak moments recorded for the WT subjects in this study (see Appendix E) were similar to the data provided by Taylor and colleagues (1991) who measured concentric knee extensor moments in power athletes (Olympic and power weight-lifters, sprinters and volleyball players). Data acquired from the WT subjects was also similar to the moment values cited for other trained athletes (Alexander 1990, Westing et al. 1990). Moments recorded for the NWT subjects in this study were very consistent with results previously published for untrained healthy males (Caldwell et al. 1993, Griffin et al. 1993, Kannus and Kaplan 1991).

Strength differences between the NWT and WT groups centred around isometric and eccentric contractions with slow velocity concentric tests also showing some differences. As expected, the WT group proved stronger than the NWT group (mean peak moment, absolute peak moment and angle-specific moment) for eccentric tests of the knee extensors and knee flexors. Very few studies to date have compared eccentric strength results among individuals of different training backgrounds. However, it stands to reason that weight-trained individuals who regularly participate in resistance exercises which include an eccentric component, would be capable of generating greater eccentric moments than an active group of males due to eccentric muscle contraction specific training.

As stated above, results for WT and NWT groups examined in this study were comparable to results previously published for trained and untrained individuals (Alexander 1990, Griffin et al. 1993, Kannus and Kaplan 1991, Taylor et al. 1991, Westing et al. 1990). The group effect on angle of peak moment occurrence for eccentric knee extension demonstrated in this investigation has not previously been reported in the literature. WT individuals reached peak moments further into the range of motion (65-75°) with eccentric tests as compared to the NWT individuals whose peaks occurred between 58-70° knee flexion. The WT subjects were able to generate greater eccentric knee extensor moments over a larger range of motion and reached peak eccentric moments later in the movement. This may be due to differences in neural recruitment strategies, mechanical factors and muscular influences related to the different training backgrounds of participants in the two groups.

Angle of peak moment occurrence was also found to exhibit a velocity effect for eccentric knee extension. For both groups, peak knee extensor moments were attained earlier in the range of motion with increasing velocity of eccentric contraction. This result has not frequently been reported in the literature, but is consistent with results previously published by Westing and Seger (1989). Of note, no significant group differences were observed in angle-specific moment or angle of peak moment occurrence for knee flexor eccentric moments. However, the p-values for these tests were verging on being significant and the study may not have had enough power to detect these differences, if they did in fact exist. Different neural recruitment strategies employed by the subjects in the two groups may have affected the generation of eccentric knee extensor moments greater than flexor moments because weight-lifters tend to focus on resisted knee extension exercises to a greater extent than resisted knee flexion exercises.

No differences were noted between the groups when angle of peak moment occurrence and angle-specific moments were compared for concentric knee extension and concentric knee flexion movements. Although WT angle-specific moments were generally greater than those recorded for NWT subjects, this difference was not significant for the knee extensors or flexors. This differs from the study by Taylor and colleagues (1991) in which concentric knee extensor angle-specific moments were found to be significantly greater in the power lifting athletes as compared to the endurance athletes. It must be remembered, however, that none of the subjects included in our study were elite Olympic caliber athletes. Subjects included in the WT and NWT groups may not have differed from each other to the same extent as the participants in the study by Taylor and coworkers. Differences in the WT and NWT neural control processes and mechanical factors may not have been developed to a large enough extent to exert a substantial influence on angle of peak occurrence or angle-specific moment.

Although the WT subjects did demonstrate significantly greater strength than the NWT subjects for concentric knee extensor mean peak and absolute peak moments, no difference was detected between the groups when concentric knee flexor moment data were analyzed. This finding has not been previously documented in similar groups of subjects. This may reflect a relative emphasis on extensor training on the part of the WT participants in this study. Because the concentric knee extensor angle-specific moment and angle of peak moment occurrence data were not different from that of the NWT subjects, differences in concentric knee extension strength may have been more strictly related to mechanical factors (muscle hypertrophy) and less due to differences in neural control.

The WT group demonstrated selective greater strength than the NWT group over certain ranges of motion and for specific types of contraction. Specifically, the WT group demonstrated significantly greater strength than the NWT group over 14.7% of the knee extensor strength map and over 25.2% of the knee flexor map. This was contrary to our hypothesis that strength differences would be apparent over most of the tested strength domain. This may in part be related to the fact that our subjects were sampled by convenience and although the NWT subjects did not participate in any lower extremity weight-training, many of them were physically active in aerobic-type exercises such as jogging and cycling. That is, the majority of subjects in the NWT group were not sedentary individuals. Also important is the fact that the WT subjects trained independently and were not required to conform to any specific lower extremity weight-training program for inclusion in this investigation. The fact that greater strength differences were not seen in knee extension and knee flexion isovelocity tests of these groups may suggest that regular participation in aerobic-type activities such as jogging and cycling is associated with significant lower extremity strengthening as well as cardiovascular conditioning. Studies examining upper body strength differences between weight-trained and non-weight trained individuals may reveal greater differences.

Comparisons of strength maps generated from knee extensor and knee flexor strength assessments revealed significant differences in shape of the moment/angle/angular velocity relationship for these two major muscle groups. The topography reveralled by the strength maps has not been previously reported. The general features of the strength maps were highly consistent among individuals. The differences in shape between knee flexor and knee extensor maps are likely reflective of overall differences in neural, muscular and mechanical factors governing the production of knee joint moment. From the information provided on the strength maps, it was possible to discern the specific ranges of motion, contraction types and speeds of movement over which the WT individuals were significantly stronger than the NWT participants. Strength maps provided a more comprehensive analysis of strength than could be determined from analyses of peak moment, absolute peak moment, angle-specific moment and angle of peak moment occurrence alone.

The greatest differences in strength between the WT and NWT groups were demonstrated isometrically. This may be explained by the fact that most of the WT subjects in this investigation reported that they primarily used free-weights and accommodating resistance machines for training. Effects of training have been shown to be range of motion, velocity, contraction type and skill specific (Aagaard et al. 1994, Graves et al. 1989, Morrissey et al. 1995). Typically, weight-lifters are instructed to perform resistance exercises in a slow and controlled manner. Exercising in this way might preferentially train individuals to perform well in low velocity (concentric and eccentric) and isometric situations. This was indeed demonstrated by the strength results measured in this study. However, WT individuals also demonstrated greater strength compared to the NWT group during high velocity eccentric contractions. Strength training with high resistances and at low velocities has been shown to improve knee extensor strength at both low and high velocities of limb movement (Aagaard et al. 1994). Weight-trainers may develop an increased rate of force development and a higher acceleration capacity and may therefore be able to perform better at higher velocities as well as at lower velocities (Aagaard et al. 1994). Researchers have also noted that untrained subjects are usually generally less familiar with producing maximal eccentric contractions as opposed to concentric contractions (Morrissey et al. 1995). Through training, weight-lifters may become familiar with the sensations associated with producing sustained high intensity eccentric contractions. In this study, WT subjects may have been able to produce greater eccentric moments at mid and high velocities as compared to the NWT subjects because they were familiar with the sensations associated with this type of maximal eccentric effort. It has been suggested that learning through practicing maximal effort eccentric contractions might have a greater impact on eccentric strength as opposed to training and testing involving other types of contractions (Morrissey et al. 1995). In other words, the neural training that accompanies exposure to high intensity eccentric contractions may outweigh the muscular and mechanical factors which also influence the production of eccentric moment. Neural regulation has been shown to play an important role in eccentric moment generation. Because greater eccentric strength differences were shown to exist between the WT and NWT groups, this suggests that differences in neural control factors may have been primarily responsible for the strength differences demonstrated between the groups.

Analysis of knee flexor:extensor RJM_k/angle/angular velocity ratio maps for the WT and NWT groups provided additional information that could not be gained from typical peak moment ratio analysis. As is evident on the ratio map (Figure 10), the flexor:extensor strength relationship is highly dependent on the contraction type, joint range of motion, and speed of movement used in the comparison. Because the WT and NWT ratio maps did not reveal any substantial differences between the groups, one might assume that knee flexor:extensor muscle balance was similar between the groups. However, because coactivation of reciprocal muscle groups has been shown to occur during movements about large joints, it has been proposed that "dynamic control ratios" which portray the maximal eccentric performance of the agonist relative to the maximal concentric performance of the antagonist (or maximal eccentric performance of the antagonist relative to maximal concentric performance of the agonist) may provide a more physiologically meaningful measure of muscle balance (Dvir 1995, Dvir et al. 1989). Dvir and co-workers (1989) found that the dynamic control ratio of average eccentric knee flexor moment (mean moment recorded from 10-80° of flexion) over average concentric knee extensor moment was more sensitive in detecting differences in muscle balance than all other combinations of concentric/concentric, eccentric/eccentric and eccentric/concentric moment ratios devised to analyze knee extensor and knee flexor performance within and between limbs. The dynamic control ratio was the only ratio to show a significant difference (20%) in contralateral knee muscle balance measurements in patients with unilateral untreated completely torn anterior cruciate ligaments and uninjured contralateral knee joints. In the future, dynamic control ratio analyses of RJM_k/angle/angular velocity relationships for reciprocal muscle groups may provide the most comprehensive and functionally meaningful evaluation of muscle balance.

Conclusions

1. Peak imposed eccentric moments were shown to be linearly proportional to pre-perturbation isometric moments. Therefore, the degree of enhancement of moment associated with imposed lengthening was dependent on the relative level of activation preceding the imposed eccentric contraction. This relationship has previously been demonstrated in isolated muscle and has been attributed to the existence of a series elastic component in the muscle sarcomere. In this study, we have demonstrated that the existence of actomyosin dependent elasticity also contributes in a similar manner to eccentric moment generation in vivo.

2. The magnitude of the predicted maximum imposed eccentric moment was shown to be 150% MVC. This represented the greatest magnitude eccentric moment measured in humans to date (relative to MVC) and approached the lower limit of the range reported for this relationship in isolated muscle (1.5-1.9X maximum isometric force). The fact that the eccentric:isometric relationship measured in the step test reached levels similar to that reported in vitro suggests that the existence of actomyosin dependent series elasticity provides a significant force contribution to eccentric moment generation. With the step test, relatively large magnitude involuntary eccentric moments were produced. This was likely related to the fact that the neural regulatory system which limits voluntary eccentric moment generation was unable to exert its normal influence during the short range of motion and short duration stretches involved in the step test.

3. Maximum voluntary eccentric moments were found to be substantially lower than the step test imposed eccentric moments. This was consistent with the existence of a neural regulatory mechanism which significantly limits motor unit activation during voluntary eccentric contractions. However, with the step test, it was possible to generate high magnitude imposed eccentric moments which suggests that eccentric moments of similar magnitudes may be generated over short ranges of motion during functional activities (e.g. in landing from a leap).

4. Strength maps were used to demonstrate that WT subjects were stronger than NWT subjects for isometric, low and moderate velocity eccentric and low velocity concentric contractions of the knee extensors and flexors. The greatest differences were found over 49-95° for the knee extensors and over 5-75° range of motion for the knee flexors. Strength map analysis provided for a much more comprehensive analysis of strength over the entire tested domain than that provided by more commonly reported strength assessment techniques. Velocity, contraction-type and range of motion-specific strength differences were identified between the WT and NWT groups which were highly consistent with the effects associated with regular participation in resistance training.

5. The strength differences demonstrated between the WT and NWT groups were likely primarily attributable to differences in neural activation and not due to differences in muscle properties such as muscle hypertrophy. The fact that concentric strength differences between the groups were not as large as those demonstrated during the eccentric and isometric tests, and the fact that thigh girth was not statistically different despite different MVC generating capabilities, suggests that neural influences may have been primarily responsible for the strength differences demonstrated in this study.

Future Recommendations

Further study of the neural regulatory mechanisms which influence eccentric moment generation may provide insight into the neural mechanisms involved and about when this process(es) is evoked during human movement. This information may enhance our understanding of the mechanisms responsible for the development of delayed onset muscle soreness and/or tendinitis which have been associated with eccentric activity.

Further use of the strength maps to analyze strength differences between trained, injured and control subject groups will add to our understanding of specific velocity, contraction-type and range of motion strength gains and deficits associated with these groups. This information may allow for the development of targeted training or rehabilitation programs in order to more effectively address weaknesses.

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Appendix A - Power Analysis

The number of subjects proposed for the study was determined by means of a power analysis. The number of subjects required for the NWT group and the WT group is dependent on the variability of the parameter being assessed (peak moment) and the difference between the two groups considered to be functionally or clinically significant (Hassard 1991). The values used for the power equation were obtained by a review of the relevant literature and were based on the isovelocity parameter of peak moment for knee flexor and knee extensor concentric and eccentric tests at multi-velocities obtained in normal male populations and elite male sprinters (Alexander 1990, Hageman et al. 1988, Highgenboten et al. 1988, Westing et al. 1988). The study by Hortobagyi and Katch (1990) demonstrated that average peak moments were 35% greater in high strength subjects compared to low strength subjects for eccentric and concentric elbow flexor and extensor moments. Studies show that NWT males generate peak knee extensor moments ranging from 130-260 Nm (concentric) and 200-300 Nm (eccentric) and knee flexor moments ranging from 85-145 Nm (concentric) and 105-180 Nm (eccentric) (Hageman et al. 1988, Highgenboten et al. 1988, Westing et al. 1988). Based on these studies a difference of 50 Nm (slightly <35%) was expected between peak moments for the NWT and lower extremity WT subjects. For this study the power index was set at 2.92 (0.05 alpha one-tailed test and 0.10 beta) for a power of 90%. Various calculations were made using relevant data from previous studies of concentric and eccentric knee flexor and extensor strength tests at multi-velocities and the sample number obtained using these figures ranged from 10 to 14 (average of 12 subjects required in each group). The sample number obtained using only eccentric data for the knee flexors and extensors ranged from 12 to 23 (average of 16 subjects per group). The equation for determining sample size for studies involving two different groups (as described in Hassard 1991) was used $\{n = 2\,(\mathrm{PI\ pop.S.D.}/u_1 - u_2)^2\}$.

Based on the study by Alexander et al. (1990) which determined concentric and eccentric peak moments (Nm) of the knee flexors and extensors at 30 °/s and 230 °/s in males elite sprinters :

$n = 2\ (2.92 \times 37.5/50)^2$

$= 9.59$ or 10 subjects required in each group

Based on this study, using only eccentric knee flexor and extensor peak moments (Nm) measured at 30 °/s and 230 °/s:

$n = 2\ (2.92 \times 41.75/50)^2$

$= 11.88$ or 12 subjects required in each group

Based on the study by Hageman et al. (1988) which determined concentric and eccentric peak moments (Nm) for the knee flexors and extensors at 30 °/s and 180 °/s in male subjects:

$n = 2\ (2.92 \times 37.2/50)^2$

$= 9.43$ or 10 subjects required in each group

Based on this study, using only eccentric knee flexor and extensor peak moments (Nm) measured at 30 °/s and 180 °/s:

$n = 2\ (2.92 \times 43.675/50)^2$

$= 13.01$ or 14 subjects required in each group

Based on the study by Highgenboten et al. (1988) which determined concentric and eccentric peak moments (Nm) for the knee flexors and knee extensors at 50 °/s in males aged 25-34:

$n = 2(2.92 \times 40.21/50)^2$

$= 11.03$ or 12 subjects required in each group

Based on this study, using only eccentric knee flexor and extensor peak moments (Nm) measured at 50 °/s:

$n = 2(2.92 \times 44.08/50)^2$

$= 13.25$ or 14 subjects required in each group

Based on the study by Westing et al. (1988) which determined concentric and eccentric knee extensor peak moments (Nm) at 30 °/s, 120 °/s, and 270 °/s in male physical education students:

$$n = 2(2.92 \times 44.02/50)^2$$

$$= 13.21$$ or 14 subjects required in each group

Based on this study, using only eccentric knee extensor peak moments (Nm) measured at 30 °/s, 120 °/s, and 270 °/s:

$$n = 2(2.92 \times 57.267/50)^2$$

$$= 22.367$$ or 23 subjects required in each group

Based on the above equations, 15 subjects were recruited for each group.

Appendix B - Paraphrase and Informed Consent Form

Comprehensive Evaluation of Knee Strength in Trained and NWT Subjects
Paraphrase and Informed Consent Form
University of Manitoba 1995

Paraphrase

During functional activity and athletic pursuits muscles act by shortening, lengthening and maintaining their length to control movement and stabilize the body. Our understanding of the ability of muscles to produce force during lengthening contractions is limited. The relationships among muscle force generating capabilities during lengthening and shortening contractions at different speeds and in maintaining a stationary position are not well understood. In addition, the relationship between the strength of one muscle group and its opposing muscle group has not been well defined. This study is aimed at providing more information about human ability to produce force during lengthening contractions and about muscle balance between the major muscle groups of the thigh. This information may assist in the prevention of injuries related to muscle imbalance and provide insight into force production during lengthening contractions.

Procedure

As a subject in this study you will be asked not to partake in any form of exercise other than your regular daily living activities on the day of the testing. You will undergo a simple screening assessment. You may then be asked to warm-up for 5 minutes on a stationary bicycle before you perform 2 tests on a special device (isovelocity dynamometer) used to measure strength about your dominant knee (the one you kick a ball with). The first test ("step test") will require you to push against the stationary dynamometer arm for approximately 4 seconds until the machine bends your knee slightly. You will asked to perform maximal and submaximal effort contractions. The second test (knee strength test) will require maximal effort knee flexion and extension (bending and straightening) at different speeds over a 90 degree range of motion. The total duration of testing will be less than 2 hours.

Any and all information provided for this study will be kept confidential.

You may be asked to return for another knee step test and strength test on a separate day.

Comprehensive Evaluation of Knee Strength in Trained and NWT Subjects
Paraphrase and Informed Consent Form
University of Manitoba 1995

Risks

The risks associated with the knee step test and strength test are minimal including;

A. After maximal exertion, you may experience some discomfort in the muscles surrounding the knee joint which may last up to 72 hours after the test. This is a normal consequence of exercise and will resolve on its own.

B. Although there have not been any published reports of muscle damage during these tests, there is a remote possibility that a tear in the muscle may occur. Similar tests have been performed on athletes and NWT subjects about different joints, with and without pathology, and even after surgery without documented damage to the muscles.

C. A certain amount of discomfort may be associated with the test (as with any form of exercise). However, if obvious pain arises at any time during the test, the test will be discontinued.

You will not be identified in any published report of the results of this study. Your participation is voluntary, and you are free to withdraw at any time without prejudice. You will not receive reimbursement for participation in this study, nor will you be responsible for any costs directly related to the study.

If you have any questions or do not understand any aspect of this form, please contact,

Dr. Dean Kriellaars
School of Medical Rehabilitation
University of Manitoba
787-2289

Comprehensive Evaluation of Knee Strength in Trained and NWT Subjects
University of Manitoba 1995

Consent Form

I have read the paraphrase and understand the nature of the study including the potential benefits and risks. I have satisfied any questions that I may have had with respect to this study. I agree to participate in this study and abide by the procedural requirements.

I understand that I may withdraw from the study at any time.

Subject ______________________ Date______________________
Witness ______________________ Date______________________
Investigator ______________________ Date______________________

Appendix C - Screening Assessment for NWT Subjects

1. Name ______________________________
2. Date ______________________________
3. Date of Birth ______________________________
4. Height ______________________________
5. Weight ______________________________
6. Maximal circumference of thigh ______________________________
7. Which leg would you kick a ball with? R or L
8. Have you participated in any elite/competitive sports in the past 5 years?
9. Have you participated in any lower extremity weight training greater than 2 times per week in the past 5 years?
10. Do you exercise regularly? If so, what type of activity do you participate in? How long are your workouts and how frequently do you exercise?
11. Have you ever injured the leg you kick a ball with? If yes, specify type of injury.
12. Do you have any restriction in movement of your "kicking" leg?
13. Do you have any cardiovascular problems (e.g. dizziness, high blood pressure, pain in chest) or any other medical conditions (e.g. arthritis) which might affect your ability to participate in the study?
14. Do you currently have any injury to your non-dominant leg?

Appendix D - Screening Assessment for WT Subjects

1. Name ______________________________________
2. Date ______________________________________
3. Date of Birth ______________________________________
4. Height ______________________________________
5. Weight ______________________________________
6. Maximal circumference of thigh ______________________________________
7. Which leg would you kick a ball with? R or L
8. Have you ever injured the leg you kick a ball with? If yes, specify type of injury. ____________
9. Do you have any restriction in movement of your "kicking" leg?
10. Do you have any cardiovascular problems (e.g. dizziness, high blood pressure, pain in chest) or any other medical conditions (e.g. arthritis) which might affect your ability to participate in the study?
11. Do you currently have any injury to your non-dominant leg?
12. Have you participated in regular lower extremity weight training greater than 2 times per week in the past 5 years?
13. Do you exercise regularly? If so, what type of activity do you participate in? How long are your workouts and how frequently do you exercise?
14. Do you currently participate in weight-training for knee extension? If yes, please specify type of exercise, amount of weight used, repetitions and sets performed, and frequency of training.
15. Do you currently participate in weight-training for knee flexion? If yes, please specify type of exercise, amount of weight used, repetitions and sets performed, and frequency of training.
16. Are you currently able to perform a single squat (knee flexion 90° or less) with a barbell weight corresponding to 150% of your body weight?
17. Have you ever used performance enhancing drugs? If yes, please specify types of drugs used, dosage of drugs consumed and period of time spent using each drug.

Appendix E - RJM $_K$/Angular Velocity Non-normalized values

Extension			Angular Velocity									
			-250	-200	-150	-100	-50	50	100	150	200	250
NWT	MEAN		243.95	234.50	238.02	255.27	268.07	219.51	196.14	179.39	165.12	155.83
		SE	14.15	11.80	13.90	10.68	14.32	9.54	8.02	9.75	6.65	5.22
	BEST		264.63	250.12	249.69	270.34	286.02	231.91	208.09	190.00	175.89	162.21
		SE	16.62	13.22	14.05	11.63	14.69	10.67	8.38	9.97	6.32	5.17
	ANGSPEC		206.65	190.84	189.11	227.95	242.62	206.59	185.55	159.05	152.85	138.57
		SE	17.05	15.74	13.85	8.84	15.57	8.29	9.14	8.21	6.49	5.98
	ANGPEAK		60.34	58.98	58.82	70.04	70.09	70.54	65.74	62.61	60.54	60.20
		SE	1.62	2.35	2.20	1.37	1.54	1.52	1.61	1.42	1.23	1.02
WT	MEAN		256.70	267.43	275.84	286.79	302.45	244.41	216.08	197.32	173.42	163.78
		SE	17.27	17.00	19.96	19.84	19.92	13.44	12.28	13.44	10.46	9.22
	BEST		277.93	294.67	294.08	307.86	322.15	261.43	228.85	208.18	182.27	173.30
		SE	18.91	20.13	21.74	20.88	19.70	13.79	12.48	13.52	10.26	9.83
	ANGSPEC		234.91	244.82	251.83	257.03	272.32	222.16	202.72	175.95	158.33	142.53
		SE	16.90	16.67	19.16	20.51	20.08	13.95	11.67	11.28	8.88	7.87
	ANGPEAK		66.37	65.36	65.60	69.87	75.41	72.40	62.78	60.56	60.19	59.88
		SE	3.20	2.99	2.95	3.58	1.93	1.70	2.60	1.94	2.07	1.73

Appendix E (cont'd)

Flexion

			Angular Velocity									
			-250	-200	-150	-100	-50	50	100	150	200	250
NWT	MEAN		129.03	127.98	128.97	124.93	124.18	100.68	94.04	87.23	80.34	75.65
		SE	7.69	8.00	9.34	9.74	10.22	4.96	4.00	4.08	3.55	3.31
	BEST		138.97	134.84	134.87	132.69	134.49	106.40	98.77	93.04	84.26	80.13
		SE	8.02	8.71	9.78	9.69	11.14	5.31	4.33	4.24	3.64	3.69
	ANGSPEC		121.25	122.89	121.47	132.94	113.15	93.83	86.47	76.17	72.76	71.02
		SE	7.85	7.70	8.89	16.26	9.38	4.69	4.35	3.60	3.60	4.11
	ANGPEAK		27.25	25.59	29.06	25.59	27.38	27.17	27.78	33.04	37.95	37.15
		SE	3.57	2.77	3.06	3.05	5.10	3.49	3.64	3.22	3.59	2.72
WT	MEAN		145.70	146.20	143.43	138.57	144.14	115.47	101.74	90.54	86.45	79.96
		SE	7.54	7.13	7.76	7.62	7.51	6.49	6.57	5.28	4.94	4.83
	BEST		156.58	153.55	151.60	148.05	154.43	121.66	106.83	95.19	89.91	83.60
		SE	7.26	6.90	7.71	7.74	7.51	7.24	7.08	5.51	5.29	4.83
	ANGSPEC		138.07	139.97	136.15	131.07	135.17	106.26	92.58	77.37	75.54	72.28
		SE	7.10	6.66	7.40	6.90	7.38	5.95	6.24	4.26	5.66	5.94
	ANGPEAK		25.47	20.59	24.50	24.58	20.96	24.27	26.63	29.94	36.91	34.83