The stretch-shortening cycle of the quadriceps femoris muscle group measured by isokinetic dynamometry

Kevin M. Helgeson
The University of Montana

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THE STRETCH-SHORTENING CYCLE OF THE QUADRICEPS FEMORIS MUSCLE GROUP MEASURED BY ISOKINETIC DYNAMOMETRY

By

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B. S., University of Montana, 1986

Presented in partial fulfillment of the requirements for the degree of

Master of Science

University of Montana, 1992

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Richard I. Cajochen
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Co-Chair, Board of Examiners

Dean, Graduate School

Feb. 1, 1992
Date
The purpose of this study was to measure the stretch-shortening cycle of the quadriceps femoris muscle group. Twenty-four volunteer subjects, 12 men and 12 women, participated in one test session, five men and five women also participated in a retest session to examine the reliability of the test. A concentric contraction of the left quadriceps was tested on a Biodex isokinetic dynamometer under three conditions: I. passive stretch before a concentric contraction, II. isometric preload before a concentric contraction and III. eccentric preload before a concentric contraction. Conditions II and III showed a significant increase in torque production compared to condition I (p < .01). No difference was found in work for the three conditions. A significant difference was found for all three conditions between the men and women, with men producing more peak torque and work. The women were able to produce a greater percent increase in torque from condition I compared to the III, indicating a greater utilization of stored elastic energy. The testing protocol was found to have high reliability. This testing protocol could be used to further study the stretch-shortening cycle in the quadriceps femoris muscle group.
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INTRODUCTION

Exercise to train or rehabilitate a muscle group should be designed to reproduce the type of contraction that the muscle group will undertake in a functional activity. The stretch-shortening cycle (SSC) is a functional contraction of a muscle that occurs when a muscle contracts eccentrically, or as it lengthens, and then immediately contracts concentrically. In human movement the SSC is used in walking and running where impact from gravitational forces cause lengthening of lower extremity muscles which immediately contract concentrically. As a result, this concentric contraction can take place with greater force than if it were initiated alone. The muscles of the lower extremity use the SSC in functional activities such as running and jumping. For example, the SSC is used in jumping activities to provide a greater push-off force for more vertical height.

Testing of the SSC in lower extremity muscle groups may lead to improved training and rehabilitation programs designed to enhance functional outcomes. Objective testing of the SSC, however, has been difficult because of the lack of instrumentation and other
technical problems. The recent advancements in isokinetic
dynamometers now allows for accurate measurements of various
characteristics of muscle performance in a clinical setting.
Specifically, they can be use to measure the torque and work of
concentric, isometric, and eccentric contractions of the quadriceps
muscle group.

The purpose of this study was to use the Biodex isokinetic
dynamometer (Biodex Corp. Shirley, NY) to measure the SSC of the
quadriceps muscle group. This was accomplished by comparing the
peak torque and work of a concentric contraction of the quadriceps
muscle group of men and women under three conditions: I. a
concentric contraction with no preload, II. a concentric contraction
preceded by an isometric preload, and III. a concentric contraction
preceded by an eccentric preload. The first null hypothesis was that
the peak torque and work of a concentric contraction would not
differ significantly among the three conditions. The second null
hypothesis was that the peak torque and work during the three
conditions would not be significantly different between genders.
OPERATIONAL DEFINITIONS

The following operational definitions were used:

STRETCH-SHORTENING CYCLE - A functional contraction cycle of skeletal muscle that includes an eccentric contraction immediately before a concentric contraction.

CONCENTRIC CONTRACTION ALONE - A shortening of contracting skeletal muscle that is preceded by a passive stretch of the muscle.

ISOMETRIC/CONCENTRIC CONTRACTION - The muscle is passively stretched followed by an isometric contraction for less than one second and then a concentric contraction.

FOOT-POUNDS - A measure of torque production.

PEAK TORQUE - The greatest amount of torque produced in the concentric contraction.

WORK - The amount of torque produced during the concentric contraction times the distance traveled during the contraction.
ASSUMPTIONS

The normal, healthy volunteers exhibited a maximal contraction under each testing condition on the isokinetic dynamometer.
REVIEW OF LITERATURE

The SSC in Isolated Muscle

Changes in muscle performance during the SSC have been measured in isolated muscle. Edman et al. found an increase in force production during a concentric contraction from single muscle fibers after the muscle was stretched when compared to isometric contractions of the muscle at the same length. Cavagna et al. measured the force produced in a muscle undergoing a concentric contraction after an isometric contraction and immediately after being stretched while contracted. The speed, amount of shortening, and initial length of the muscle were held constant. The researchers found that the force of the concentric contraction was greater after being stretched, compared to the isometric contraction alone. The amount of work done was also greater after being stretched. Cavagna et al. also found that the concentric contraction must immediately follow the stretch or the force and work of the contraction were diminished. These studies indicated that an eccentric preload immediately before a concentric contraction will
enhance or increase the force production and work of the concentric contraction.

The SSC in Human Muscle

Studies of the SSC of human muscle groups are numerous. Most of these studies consisted of measuring a vertical jump under different conditions. These were usually 1.) a static jump, in which a person stands in a squatting position and jumps with no countermovement of the limbs; 2.) countermovement jump in which a person is allowed to flex the lower extremities before extending them in a countermovement manner before jumping, and 3.) drop jumping in which the person jumps off steps of varying heights and then immediately performs a vertical jump. The countermovement and drop jump conditions allow for a stretch or an eccentric pre-loading of the lower extremity muscles before they contract concentrically to perform a vertical jump. Both of these conditions consistently produced a higher vertical jump and greater work by the muscles when compared to a static jump. The drop jump condition applies a greater eccentric load to the extensor muscles and results in even greater vertical heights than the countermovement jump, up to a certain height of the drop.
These studies of vertical jumping have shown that a greater speed of stretching and a shorter time between the stretching and concentric contraction phase enhances the height of the jump and the resulting work output.\textsuperscript{6,21} Electromyographic activity of the quadriceps muscle group was found to be slightly increased in the countermovement and drop jump conditions when compared with the static jump.\textsuperscript{8,10}

Training studies have demonstrated that plyometric training, a method that employs the SSC, can improve athletic performance.\textsuperscript{5,13,32} This type of training was first introduced by Verhoshanski for use by Russian track athletes.\textsuperscript{37} He devised training programs that allowed the greatest "dynamic conformity" to athletic performance, thus allowing a high degree of "reactive ability" in which strength and speed were developed.\textsuperscript{7} Usually a series of jumping and bounding exercises are used in this type of training. Plyometric training programs are routinely used to improve athletic performance, but it is unclear what characteristics of movement are improved by this type of training.
Factors That Contribute to the SSC

Early hypotheses of why a muscle produces greater work in a concentric contraction when it has been immediately preceded by an eccentric contraction enter on the elasticity of the muscle. The elastic elements of the muscle could store energy from an eccentric contraction (negative work) and be used in a concentric contraction. By changing the amount of negative work, subsequent changes were observed in the positive work (concentric). The elasticity of muscle is related to its mechanical structure of the visoelastic and the contractile components. The visoelastic components are either in parallel or in series with the contractile components. The parallel elastic components include the sarcolemma and connective tissue of the endomysium, perimysium, and epimysium. The series elastic components of the tendon and stable cross-bridges between the actin and myosin filaments are believed to be more important than the parallel elastic components in contributing to force production. Huxley and Simmons hypothesized that the heads of the myosin filaments, specifically the S-2 unit of the heavy meromyosin molecule are rocked backward into a position of greater potential energy in a muscle that is stretched or eccentrically preloaded.
Because the cross-bridge lifetime is limited, a small stretch and a short time between the stretch and the concentric contraction are advantageous for using the stored elastic energy.

Komi has related the stiffness of a muscle to the SSC. Stiffness of a muscle is measured by the change in tension divided by the change in length, an increase in muscle stiffness would further improve the SSC. This force-length relationship can be influenced by three factors when the SSC is trained. First, hypertrophy and subsequent motor unit activation of a muscle could increase its stiffness. Second, the increase in muscle spindle discharge could influence the length-feedback component of the muscle, and third, inhibition of the Golgi tendon organ could influence the force-feedback component of the muscle, both serving to increase stiffness.

Bobbert has discounted the effect of elasticity or the amount of absorbed energy stored in series elastic components that contributes to a concentric contraction. He has related the amount of stored energy to the force of a muscle. Bobbert is unclear whether he considers the actin-myosin cross-bridges series elastic components when he illustrates the potentiation of a muscle during the SSC.
Figure 1. Schematic representation of the actin-myosin crossbridges under three states: A. resting state, B. stretching state, C. concentric contraction.
Potentiation was hypothesized as the backward rotation of cross-bridge heads to a position in which they exerted more force. He also explored the increase in stretch and spinal reflexes contribution during the SSC. Komi pointed out that the elastic and the myoelectrical components cannot be separated because an increase in myoelectric potentiation will result in increased elastic potentiation.\textsuperscript{23}

A study of the influence of the SSC on fatigue of a muscle found that fatigue was less in a muscle that was pre-stretched before contracting compared to a muscle that contacted isometrically only.\textsuperscript{15} Extra work from the SSC was presumed to result from sources other than cross-bridge cycling. The first one-third of the concentric contraction of the SSC had greater increases in force production compared to the second two-thirds. The first one-third also had less fatigue compared to the second two-thirds of the contraction. This implies that the SSC acts to protect against fatigue.

\textbf{Isokinetic Dynamometers}

The ability to measure the performance characteristics of human muscle groups has increased since the development of
isokinetic dynamometers. The dynamometers are used to measure both the concentric and eccentric torque production of various muscle groups. Much is known about the concentric muscle contractions of the knee extensors and flexors.\textsuperscript{34,36,38} In addition, recent studies have reported the eccentric contraction characteristics of the knee extensors and flexors,\textsuperscript{14,16} and what effect an eccentric training program will have on these muscle groups.\textsuperscript{4,16,20,30} The use of isokinetic dynamometers has become an easy and reliable method for measuring the strength in the quadriceps muscle group. Specifically, the Biodex dynamometer has been shown to provide reliable measurements of peak torque and work for concentric and eccentric knee extension and flexion at various speeds.\textsuperscript{18,25,35} No studies have reported using an isokinetic dynamometer to measure the SSC of the quadriceps femoris muscle group.

The isokinetic dynamometer has been used to measure the SSC in the ankle plantarflexor muscle group.\textsuperscript{33} Torque production was significantly greater during a concentric contraction after an eccentric preload at speeds of 120 and 240 degrees per second when compared to a concentric contraction with no pre-load. The electromyographic activity in the plantarflexors was significantly less.
during the concentric contraction after an eccentric preload. A study of elbow flexors during continuous eccentric-concentric contractions on an isokinetic dynamometer found no significant increase in torque production compared to a concentric contraction alone. The SSC was probably not elicited on the isokinetic dynamometer during the continuous eccentric-concentric contractions: the elbow flexors, not normally being weight bearing muscles, may not be trained to utilize the SSC. The SSC could be measured in the quadriceps muscle group using a short eccentric contraction immediately followed by a concentric contraction.
METHODS

Subjects

Twenty four volunteer subjects, 12 women and 12 men, were recruited. Subjects were 19-35 years of age with no current left lower extremity pathologies, neurological problems, or other conditions that could be aggravated by the testing protocol or confound the test results. One subject was eliminated from the study when the testing protocol caused knee pain that inhibited her from giving a maximum effort. The subjects' age, height, weight and activity level were recorded. A body mass index (wt/ht^2) was computed for each subject. All subjects had an index of less than 30, which eliminated obese subjects in the sample. Descriptive statistics of the subjects are reported in Table 1. The subjects signed an informed consent approved by the Institutional Review Board of the Use of Human Subjects in Research at the University of Montana. They were requested to refrain from unusual activities or vigorous exercise 24 hours before their testing session.
Table 1. Means, standard deviations, and ranges of subject's age, mass, and height.

<table>
<thead>
<tr>
<th></th>
<th>Age</th>
<th>Weight(kg)</th>
<th>Height(cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>All subjects (n=24)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>28.7</td>
<td>68.6</td>
<td>171</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>5.4</td>
<td>11.7</td>
<td>13.1</td>
</tr>
<tr>
<td>Range</td>
<td>19-35</td>
<td>48-86</td>
<td>121-185</td>
</tr>
<tr>
<td><strong>Men (n=12)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>29.6</td>
<td>78.0</td>
<td>179</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>4.5</td>
<td>6.1</td>
<td>3.7</td>
</tr>
<tr>
<td>Range</td>
<td>20-35</td>
<td>68-86</td>
<td>173-185</td>
</tr>
<tr>
<td><strong>Women (n=12)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>27.8</td>
<td>59.2</td>
<td>163</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>6.2</td>
<td>7.4</td>
<td>14.8</td>
</tr>
<tr>
<td>Range</td>
<td>19-35</td>
<td>48-68</td>
<td>121-178</td>
</tr>
</tbody>
</table>

**Instrumentation**

A Biodex B-2000 dynamometer (Biodex Corp. Shirley, NY) at Western Montana Sports Medicine and Fitness Center was used for testing. The Biodex was connected to a microcomputer and interfaced with Biodex Software 2.4. Calibration of the Biodex dynamometer was checked after testing each subject. The Biodex passive mode at 60 degrees per second was used in the practice and testing sessions.
PROCEDURES

Practice Session

Each subject participated in a practice session before the test session. The practice session consisted of left knee extension contractions with the Biodex on a continuous passive mode. The knee was passively flexed from 0 degrees of knee flexion (full extension) to 90 degrees of flexion, with the lever arm at a speed of 60 degrees per second. The subject was instructed in three conditions: 1.) concentric contraction of the quadriceps muscle group from 90 degrees to 0 degrees of flexion, 2.) the lever arm paused for one second at 90 degrees of flexion, while the subject started an isometric contraction and continued that contraction concentrically as the lever arm moved into full extension, and 3.) as the lever arm moved from knee extension to flexion the subject initiated an eccentric contraction between approximately 45 degrees to 90 degrees of flexion and then continued with a maximal concentric contraction as the lever arm moved back into full knee extension.

Verbal instructions and manual resistance were given to aid in learning these three conditions. The subject also was allowed to view the computer screen for feedback of their performance. After the
subject learned to give maximal contractions for all three conditions they were scheduled for testing within 3-5 days.

**Testing Session**

The subject was allowed a 5 minute warm-up on a Fitron (Cybex Corp, Ronkonkoma, NY) stationary bicycle at a light intensity (less than 600 kpm). The subject's left lower extremity was then tested randomly under the same three conditions as taught during the practice session. A scripted amount of encouragement was given to each subject during the test session with no feedback from the computer screen.

The subject was seated on the Biodex chair with the hip flexed to 100 degrees, with standard stabilization strapping across the distal thigh, waist, and chest. The bottom of the lever arm pad was placed just proximal to the medial malleolus. Hand placements were limited to grasping the waist stabilization strap.

The subject was allowed 3 submaximal contractions of the quadriceps muscle group at the beginning of the test condition to re-familiarize him or her with the test conditions. The subject was given 5 maximal contractions in each test condition. Between each condition the subject was given a one minute rest. The best peak
torque and the best work contraction of the five test contractions of each test condition were collected for data analysis.

Ten of the subjects, 5 men and 5 women, were selected randomly for a retest in 3-5 days. They were retested in the same order of conditions as during the test session. The test-retest measures were used to determine the reliability of the testing protocol.

**DATA ANALYSIS**

The Biodex software program 2.4 (Biodex, Inc. Shirley, NY) provided the measures of peak torque, standardized peak torque (peak torque divided by body weight), work and standardized work (work divided by body weight). Descriptive statistics of the means, standard deviations and ranges were determined for each of the four measures for the three conditions. A multivariate analysis of variance (MANOVA; pillai trace) for repeated measures was used to examine differences among the three conditions for each measure. Significant F-ratios were followed by univariate F-tests to examine differences between conditions. Pearson correlation coefficients (r)
and Intraclass Correlation Coefficients (ICC)\textsuperscript{3} were used to determine the reliability of measuring the peak torque and work for the 10 subjects.

A two-way MANOVA was used to determine differences between the men and women among the four measures and the three test conditions. Univariate F-tests were used to contrast cell differences. A MANOVA for repeated measures was used to examine the differences among the conditions for each measure for the men alone, and then for women alone. Data were analyzed with the SYSTAT software statistical package (SYSTAT Inc., IL, USA) and a microcomputer. The 0.05 level of significance was used for all statistical measures.
RESULTS

Descriptive statistics of each measure for all subjects (n=24), for the men alone (n=12) and for the women alone (n=12), for the three conditions (I. concentric alone, II. isometric preload, III. eccentric preload) are reported in Tables 2-5, respectively.

The MANOVA for peak torque values (n=24) showed significant differences among the three conditions (F=22.25, p<.001). Post-hoc analysis revealed a significant difference between the concentric and isometric preload conditions, (F=14.97, p<.001) and between the concentric and eccentric preload conditions (F=44.41, p<.001). The concentric peak torque following the isometric preload and the eccentric preload conditions were not significantly different (Figure 2a). The standardized peak torque was also significantly different among the three conditions (F=21.41, p<.001). As with the peak torque, post-hoc analyses showed significant differences between the concentric and isometric preload conditions (F=11.43, p<.001) and between the concentric and eccentric preload conditions (F=43.40, p<.001). The MANOVA for work and standardized work showed no significant differences among the three conditions (Figure 2b).
Figure 2. Mean peak torque (A) and work (B) for the three conditions: C. Concentric Alone, I. Isometric Preload, E. Eccentric Preload for all subjects (n=24).
Table 2. Means, Standard Deviations, and Ranges of Peak Torque (ft.-lbs.) of the three conditions.

<table>
<thead>
<tr>
<th></th>
<th>I.</th>
<th>II.</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>All subjects (n=24)</strong></td>
<td>Mean</td>
<td>171.7</td>
<td>186.6</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>50.4</td>
<td>59.9</td>
</tr>
<tr>
<td></td>
<td>Range</td>
<td>99-253</td>
<td>108-277</td>
</tr>
</tbody>
</table>

|                  | **Men (n=12)** | Mean | 219.4 | 239.2 | 231.1 |
|                  | Standard Deviation | 32.4 | 33.5 | 29.0 |
|                  | Range | 135-253 | 157-277 | 164-268 |

|                  | **Women (n=12)** | Mean | 128.4 | 134.1 | 142.2 |
|                  | Standard Deviation | 13.3 | 18.5 | 15.7 |
|                  | Range | 99-142 | 108-177 | 107-171 |
Table 3. Means, standard deviations, and ranges for standardized peak torque* for the three conditions.

<table>
<thead>
<tr>
<th></th>
<th>L</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>All subjects (n=24)</td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
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<tr>
<td></td>
<td>113.0</td>
<td>122.3</td>
<td>122.3</td>
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<tr>
<td>Standard Deviation</td>
<td>19.2</td>
<td>27.1</td>
<td>18.6</td>
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<tr>
<td>Range</td>
<td>84-141</td>
<td>85-157</td>
<td>88-159</td>
</tr>
<tr>
<td>Men (n=12)</td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
</tr>
<tr>
<td></td>
<td>125.7</td>
<td>139.8</td>
<td>135.0</td>
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<tr>
<td>Standard Deviation</td>
<td>16.9</td>
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<td>Range</td>
<td>84-141</td>
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<td>101-159</td>
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<tr>
<td>Women (n=12)</td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
</tr>
<tr>
<td></td>
<td>100.3</td>
<td>104.9</td>
<td>109.9</td>
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<tr>
<td>Standard Deviation</td>
<td>11.6</td>
<td>23.6</td>
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<tr>
<td>Range</td>
<td>86-121</td>
<td>85-154</td>
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* peak torque/body mass
Table 4. Means, standard deviations, and ranges of work (ft.-lbs.) for the three conditions.

<table>
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<td>Mean</td>
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<td>155.3</td>
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<td>Standard Deviation</td>
<td>50.5</td>
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<td>Range</td>
<td>90-249</td>
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<td>Men (n=12)</td>
<td>Mean</td>
<td>200.3</td>
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<td>35.7</td>
<td>41.5</td>
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<tr>
<td></td>
<td>Range</td>
<td>123-249</td>
<td>123-254</td>
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<tr>
<td>Women (n=12)</td>
<td>Mean</td>
<td>117.7</td>
<td>110.5</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>17.9</td>
<td>16.2</td>
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<tr>
<td></td>
<td>Range</td>
<td>90-142</td>
<td>89-137</td>
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</tbody>
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Table 5. Means, standard deviations, and ranges of standardized work* for the three conditions.

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<td>101.9</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>20.4</td>
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<td>66-143</td>
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<td>22.7</td>
</tr>
<tr>
<td></td>
<td>Range</td>
<td>76-141</td>
<td>76-143</td>
</tr>
<tr>
<td>Women (n=12)</td>
<td>Mean</td>
<td>90.2</td>
<td>87.0</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>9.2</td>
<td>13.1</td>
</tr>
<tr>
<td></td>
<td>Range</td>
<td>81-105</td>
<td>66-113</td>
</tr>
</tbody>
</table>

*work/body
Reliability measures of the three conditions for peak torque and work are shown in Table 6. The correlation coefficients for all measures ranged from ICC= 0.86-0.99 and Pearson r=0.96-0.98.

<table>
<thead>
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<th></th>
<th>I,</th>
<th>II,</th>
<th>III,</th>
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<tr>
<td>Peak Torque ICC</td>
<td>.98</td>
<td>.97</td>
<td>.98</td>
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<tr>
<td>Pearson r</td>
<td>.98</td>
<td>.97</td>
<td>.98</td>
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<tr>
<td>Work ICC</td>
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<td>.94</td>
<td>.86</td>
</tr>
<tr>
<td>Pearson r</td>
<td>.97</td>
<td>.96</td>
<td>.97</td>
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</table>

The MANOVA showed a significant difference between the men and women for the peak torque (F=29.99, p<.001). Post-hoc analysis showed a significant difference for all three conditions; I. concentric, (F=73.34, p<.001), II. isometric preload, (F=90.34, p<.001), and III. eccentric preload (F=87.34, p<.001). Significant differences were also found between the men and women for the standardized peak torque (F=6.27, p<.001). Post-analysis again showed significant differences for each condition, I. (F=18.26,p<.001), II. (16.63, p<.001), and III. (F=19.82, p<.001) (Table 9).

Work measures between the men and women were
significantly different (F=16.15, p<.001). The post-hoc analysis revealed a significant differences for the three conditions, I. (F=51.36, p<.001), II. (F=48.51, p<.001), and III. (F=47.98, p<.001). The MANOVA for the standardized work also showed a significant difference between the men and women (F=5.67, p<.05). Post-hoc analyses again showed significant differences for the three conditions; I. (F=18.38, p<.001), II. (F=15.47, p<.001), and III. (F=15.54, p<.001) (Table 9).

For the men alone, a MANOVA revealed a significant difference among the three conditions for peak torque (F=13.16, p<.001). The post-hoc analyses showed significant differences between the concentric and isometric preload conditions (F=28.04, p<.001) and between the concentric and eccentric preload conditions (F=16.43, p<.001). Standardized peak torque was also significantly different among the conditions (F=11.78, p<.001). The post-hoc analyses again showed significant differences between the concentric and isometric preload conditions (F=25.16, p<.001) and between the concentric and eccentric preload conditions (F=14.73, p<.001). Work and standardized work for the men showed no significant differences among the three conditions.
For the women, a MANOVA showed a significant difference for peak torque measures among the three conditions ($F=18.62, p<.001$). The post-hoc analysis showed a significant difference between the concentric and eccentric preload conditions only ($F=40.11, p<.001$). Standardized peak torque showed a significant difference among the conditions ($F=15.46, p<.001$). The post-hoc analysis again showed a significant difference between the concentric and eccentric preload conditions only ($F=33.97, p<.001$). For the work, a significant difference was found among all conditions ($F=5.05, p<.05$). The post-hoc analyses showed significant differences between the concentric and eccentric preload conditions ($F=8.62, p<.05$) and between the isometric and eccentric preload conditions ($F=9.25, p<.05$). The concentric and isometric preload conditions did not differ. Standardized work also showed a significant difference among the conditions ($F=5.28, p<.05$), and as with the work measures, significant differences were found between the concentric and eccentric preload conditions ($F=9.99, p<.05$) and between the isometric and eccentric preload conditions ($F=5.98, p<.05$), but not between the concentric and isometric preload condition.
Table 7. Significant differences for peak torque means across the three conditions: I. concentric alone, II. isometric preload, and III. eccentric preload for all subjects (n=24), men (n=12), and women (n=12). * p< .001

<table>
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<td>I - III *</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Men</td>
<td>219.4</td>
<td>239.2</td>
<td>231.1</td>
</tr>
<tr>
<td>I - II *</td>
<td></td>
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<tr>
<td>I - III *</td>
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<td></td>
<td></td>
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<tr>
<td>Women</td>
<td>128.4</td>
<td>134.1</td>
<td>142.2</td>
</tr>
<tr>
<td>I - III *</td>
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</tr>
</tbody>
</table>

Table 8. Significant differences for work means across the three conditions: I. concentric alone, II. isometric preload, and III. eccentric preload for all subjects (n=24), men (n=12), and women (n=12). * p< .05

<table>
<thead>
<tr>
<th></th>
<th>I.</th>
<th>II.</th>
<th>III.</th>
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<tbody>
<tr>
<td>All subjects</td>
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<tr>
<td>Men</td>
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<tr>
<td>Women</td>
<td>117.7</td>
<td>110.5</td>
<td>123.8</td>
</tr>
<tr>
<td>I - III *</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>II - III *</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 9. Significant differences between men (n=12) and women (n=12) for peak torque and work means across three conditions: I. concentric alone, II. isometric preload, and III. eccentric preload. *p< .001

<table>
<thead>
<tr>
<th>Peak Torque</th>
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<td>219.4</td>
<td>239.2</td>
<td>231.1</td>
</tr>
<tr>
<td>Women -</td>
<td>128.4</td>
<td>134.1</td>
<td>142.2</td>
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<tr>
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<td>*</td>
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</table>

<table>
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<th>Work</th>
<th>I.</th>
<th>II.</th>
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<tr>
<td>Men -</td>
<td>200.3</td>
<td>200.1</td>
<td>201.8</td>
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<tr>
<td>Women -</td>
<td>117.7</td>
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</table>
DISCUSSION

The results showed a significant increase in concentric peak torque during the eccentric preload condition compared to the concentric contraction with no preload. This indicates that the eccentric preload of the quadriceps muscle group increased the torque production of the concentric contraction of the muscle group. Also, the isometric preload condition resulted in greater concentric peak torque than the concentric contraction alone. The mean peak torque was the same for the eccentric and isometric preload conditions. This finding allows the null hypothesis to be rejected and concurs with the studies of Svantesson et al.\textsuperscript{33} and deHaan et al.\textsuperscript{15} who also found an increase in force production with an eccentric preload.

The isometric and eccentric preload conditions both resulted in an increased force production during the concentric phase of the contraction. An eccentric preload is used in functional activities where the SSC is utilized. During the SSC the muscle elongates to a point of isometry (when the muscle force equals the external force causing the lengthening of the muscle) and then begins to shorten.
during the concentric contraction. The preload of a muscle, whether isometric or eccentric, can influence the following concentric contraction by increasing force production and may also be important for producing force sooner in the contraction. This will be explored with the discussion of how work is produced during these two preload conditions.

Work levels across the three conditions were not significantly different. But, the shape of the torque curve of the concentric contraction after the isometric and eccentric preload conditions appears to differ from the torque curve shape of the concentric contraction alone. (Figure 3). The work produced in the three conditions appears different, and this observation may provide further insight into the SSC. The characteristics of the isometric and eccentric preload conditions showed that most of the torque occurred in the early portion of the contraction and then dropped rapidly. The concentric contraction alone required more time and range of motion to peak torque and showed a slower drop in torque. Even so, all conditions produced similar levels of work. The SSC provided more torque during the concentric contraction and may be able to produce the torque more quickly in the range of motion for activities which
Figure 3. Sample torque curves of the three testing conditions: I. Concentric alone, II. Isometric preload, and III. Eccentric preload.
require instantaneous force production. Measures of work or characteristics of torque curves have not been addressed in other studies of the SSC using an isokinetic dynamometer.\textsuperscript{33, 39}

Significant differences were found between the men and women for peak torque and work, which allows for rejection of the second null hypothesis. This was expected due to the larger body weight of the men. But when the measures were standardized to body weight a significant difference still existed between men and women. The two groups were of similar age and activity level. This difference cannot be explained completely, but it could perhaps be related to a difference in connective tissue characteristics, muscle stiffness and the ratio of fast twitch to slow twitch muscle fibers in the quadriceps muscle group between men and women. Absolute measures of strength of the lower extremities in women have been estimated at 70 percent of men.\textsuperscript{22} There are some indications that men may have a greater ratio of fast twitch fibers in the vastus lateralis but no conclusive evidence exists that there is a significant difference in fast and slow twitch muscle fibers in the quadriceps muscle group of men and women.\textsuperscript{22, 27, 31} Differences between men and women in lower extremity strength have been explained by
body sizes, lean body mass, and muscle cross sectional area. Maughan et al. also discussed the difference in angle of pennation of the quadriceps muscle group in men and women. Men generally have a lesser angle of pennation or a more vertical alignment of muscle fibers in the quadriceps muscle group allowing a more direct pull through the patellar tendon with knee extension. This is a more efficient contraction of the quadriceps muscle compared to women with a greater angle of pennation. The women, however, may be able to utilize this greater angle of pennation in the SSC, which will be discussed later.

The results of this study are similar to other in vivo studies of the SSC in human skeletal muscle. In these studies, vertical jumps were compared under different conditions. When a jump from the squatting position that provided only concentric work from the lower extremities was compared to a jump with an eccentric preload provided by countermovement from the lower extremities, the eccentric preload provided a significant increase in the amount of work produced and the resulting vertical jump height. Komi and Bosco found a 14% increase in work levels for men and 18% increase for women. The current study found that with an
eccentric preload the women had a ten percent increase in peak torque and a five percent increase in work, while the men only had a five percent increase in peak torque and a one percent increase in work. These results of the current study support the results of Komi and Bosco\textsuperscript{21} in that work produced during the vertical jump uses hip and knee extensors with ankle plantarflexors. The current study only measured one muscle group, the knee extensors, and this limitation of muscle groups may partially explain the difference in percent increases between the two studies.

Komi and Bosco\textsuperscript{21} compared men and women in vertical jumping tests off a force platform. Work produced jumping off the platform was termed positive energy and work produced down into the platform, during a countermovement, was termed negative energy. They found that men could jump significantly higher and produce greater positive work during their jump than women. When they measured the negative work produced during an eccentric preload and calculated the resulting increase in positive work, the women had a 21% increase compared to 13.5% for the men. When the amount of negative work utilized during the jump was compared, the women were found to use 90%, the men only using 49%. These
differences could not be fully explained even when the differences in body mass were considered. Somehow the women in the study were able to utilize a greater amount of stored elastic energy.\(^{21}\)

The amount of negative work during the eccentric preload was not considered in the current testing protocol, but this could possibly be measured. The current study found that the women had a 10.7\% increase in peak torque and a 5.2\% increase in work for the eccentric preload condition compared to the concentric contraction alone. The men had a 7.5\% increase in peak torque and a 1.0\% increase in work. This finding provides another indication that women may utilize stored elastic energy better than men. Maughan et al.\(^{27}\) have hypothesized that differences between men and women in their angle of pennation of the quadriceps muscle group contribute to differences in strength of this muscle group. Women generally having shorter femurs would have a greater angle of pennation, this could allow greater stretch through the muscle group during an eccentric preload and a greater rebound of the muscle with a concentric contraction.

The men had significant differences between the concentric contraction alone and the isometric and eccentric preload conditions.
The isometric preload condition had the greatest mean peak torque but was not significantly greater than the eccentric preload. This concurs with a theory of greater fast twitch muscle composition in the quadriceps muscle group in men, permitting them to generate greater torque more quickly than women. There were no significant differences among the three conditions for work, which may be explained by the small differences between the measures of peak torque and the differences in the shape of the torque curves as previously discussed.

The women showed a significant difference between the concentric alone and eccentric preload conditions for peak torque, again showing the SSC was measured by isokinetic dynamometry. The work measures were significantly different between the concentric and eccentric preload conditions and between the isometric and eccentric preload conditions. The isometric preload condition had the lowest mean work output and was not significantly greater than concentric alone for peak torque. This again, could be related to a lower ratio of fast twitch muscle fibers in the quadriceps muscle group of women.

Reliability measures for peak torque and work measures were
all good as determined by ICC and Pearson r levels. This was due to the control of methodological errors. Subject positioning was held constant, testing protocol was standardized, and the subjects were allowed to practice the test protocol before the test session. This protocol for testing the quadriceps muscle group strength demonstrated a high level of reliability. The Biodex has already been determined a reliable instrument to measure concentric and eccentric contractions of the quadriceps muscle group.\textsuperscript{18,35}

The current study used a limb velocity of 60 degrees per second which was fast enough to produce the SSC, but it is probably too slow to be considered a functional speed such as in running or jumping. The velocity of the lever arm was selected primarily for subject safety and to enhance the ability to learn the testing protocol quickly. Faster velocities of eccentric preloading would be needed when compared to functional activities. Isokinetic dynamometers can be programmed for different velocities of the eccentric and concentric contractions that would come closer to the speed of functional activity. Also, the isokinetic dynamometer is an open kinetic chain device and cannot be directly related to closed kinetic chain activities such as vertical jumping.
A systematic error was entered into all three conditions. The lever arm of the dynamometer was set on a passive mode at 60 degrees per second, the subject could either resist or assist the lever arm in the direction it moved. Tests of the lever arm movement alone at 60 degrees per second showed that the lever arm produced less than two foot-pounds of torque in the extension direction. This additional torque was added to all scores of concentric contraction of the quadriceps muscle group. The lever arm was set at 60 degrees per second, which took approximately 0.32 seconds to decelerate and accelerate when changing directions at 90 degrees of flexion, which gave the lever arm momentum not contributed by the quadriceps muscle group. The software program used the limb weight, measured by the isokinetic device to decrease the influence of gravity on the limb through the flexion and extension movements.
RECOMMENDATIONS

The current study showed that the SSC of the quadriceps muscle group can be measured by isokinetic dynamometry. As a result, this testing protocol could be used to compare quadriceps femoris muscle performance on an isokinetic dynamometer to functional activities such as the vertical jump. The testing protocol of Komi and Bosco\(^1\) measured the negative and positive work of the vertical jump. This could be compared to the same measures used by the isokinetic dynamometer under similar testing conditions with eccentric preload being termed negative work and concentric contractions termed positive work. The electromyographic activity of the quadriceps muscles could also be measured during vertical jumps and compared to tests using the isokinetic dynamometer. The recent study of ankle plantarflexors found a decrease in electromyographic activity during the concentric contraction of the SSC,\(^3\) while a study of vertical jump conditions showed increased electromyographic activity in ankle plantarflexors during the concentric contraction of the SSC.\(^1\) This information indicates the need for additional studies of the SSC and electromyographic activity.
Studies of the SSC using plyometric training protocols could be measured for changes in muscle performance. Changes in torque production during concentric, eccentric, and SSC contractions could be measured on an isokinetic dynamometer and be compared to performance under vertical jump conditions. Parameters such as electromyographic activities and muscle stiffness could also be measured for changes with plyometric training. An improvement in vertical jump heights using the SSC could be achieved without a significant increase in strength of the lower extremity muscle groups. This improved performance could be related to changes in muscle stiffness or a greater potentiation of the muscle eccentric preloading. These changes in performance would be interesting to compare between men and women. Another approach would be to train the SSC in the quadriceps muscle group and see if changes are found in vertical jump conditions.
CONCLUSION

The results of this study indicated that force characteristics of the SSC can be measured reliably using an isokinetic dynamometer. The results showed a significant increase in peak torque and work for a concentric contraction of the quadriceps muscle group after an eccentric and isometric preload compared to a concentric contraction alone for all subjects (n=24). The men could produce a significantly greater amount of peak torque and work than the women. This finding also occurred when these measures were standardized of body weight. The results showed that the SSC can be measured in the quadriceps muscle group. Consequently, further study of the SSC is possible and new training methods for functional activities could be developed and examined.
REFERENCES


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APPENDIX A

INFORMED CONSENT FORM
INFORMED CONSENT

Title: The Stretch-Shortening Cycle of Skeletal Muscle Measured by Isokinetics

Investigator: Kevin Helgeson, PT (W: 251-3344, H: 728-4860)
Co-investigator: Richard Gajdosik, PhD (W: 243-4753, H: 549-0589)

I understand that I am participating in a research project titled above. This project is designed to measure the strength of my left quadriceps muscle group under three conditions using a Biodex dynamometer.

I understand my age, height, weight and activity level will be recorded and only used for research purposes. I will not be identified in the research project.

I agree to participate in a short (15 minute) practice session in which I will be instructed in the three testing conditions. Once I have learned the three conditions I will be scheduled for a testing session in 4-5 days.

I agree to wear athletic clothing for the testing session. I will be allowed a light warm-up for 5 minutes on a stationary bicycle. I will be seated on the Biodex testing chair and be comfortably strapped in to provide stabilization during testing. I will be allowed 3 practice contractions before each test condition to re-familiarize myself with the condition. I will give maximum effort in each testing condition.

I understand I may be asked to participate in a retest session to check the reliability of the tests. This will occur 4-5 days after the initial tests.

I understand I may have some muscle fatigue from the testing conditions and may have some muscle soreness 1-2 days after the test. I will be allowed at least one minute rest between each testing condition.

I understand I may ask questions about the research project. I may also know the results of my test after I have completed the test. I understand Kevin Helgeson is responsible for my welfare during the practice and testing sessions.

I understand that as a voluntary subject, I am allowed to withdraw from this study at any time.
"In the event that you are physically injured as a result of this research you should individually seek appropriate medical treatment. If the injury is caused by the negligence of the University or any of its employees you may be entitled to reimbursement or compensation pursuant to the Comprehensive State Insurance Plan established by the Department of Administration under the authority of M.C.A., Title 2, Chapter 9. In the event of a claim for such physical injury, further information may be obtained from University Legal Counsel."

I have read the above statement and thoroughly know, understand and appreciate the risks involved. I authorize Kevin Helgeson, PT to administer and conduct the tests as safely as possible and with a minimum of discomfort.

Name__________________________________________Date____________________
APPENDIX B

DATA COLLECTION FORM
DATA SHEET

NAME ________________________________ Age __________ # __________

Date of Test ____________________________ Retest

_____________________________

Height __________ inches x .0254 __________ meters

Weight __________ pounds / 2.2 __________ kilograms

Body Mass Index (Wt/Ht^2) __________

Activity Level in the past 3 months:

Exercise per week ____________________________

Types of Exercise _______________________________________

Seat ______ Lever Arm _____ LimbWeight___________

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<tr>
<td>Eccentric/Concentric</td>
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Comments:
APPENDIX C

DATA COLLECTION PROCEDURES
STEPS FOR EXPERIMENTAL SESSIONS

1. Thoroughly acquaint the subject with all procedures
2. Record height and weight of subject

3. Have subject ride Fitron stationary bicycle at moderate pace for 5 minutes

4. Seat subject on Biodex chair and adjust chair and lever arm, record position of chair and lever arm
5. Stabilize subject with strapping in a comfortable position

6. Set range of motion of Biodex for 0 to 90 degrees of knee motion
7. Have Biodex measure limb weight to correct for gravity, record this value

8. Set Biodex on passive mode and start the movement of the lever arm at 60 degrees per second

9. Instruct subject in the first testing condition and have them practice the contraction three times
   Rest 30 seconds
10. Test and record 5 maximum contractions of the first test condition
    Rest 60 seconds
10A. Verbal Instructions during each test condition.
   1. "Ready, Go"
   2. First contraction - "That's Good"
   3. Second contraction - "Keep Going"
   4. Third contraction - "Good, Two More"
   5. Fourth contraction - "One More Good One"
   6. Fifth contraction - "Stop"

11. Instruct subject in second testing condition and have them practice the contraction three times
    Rest 30 seconds
12. Test and record 5 maximum contractions of the second test condition
    Rest 60 seconds
13. Instruct subject in third testing condition and have them practice the contraction three times  
   Rest 30 seconds  
14. Test and record 5 maximum contraction of the third test condition  
15. Stop lever arm, undo strapping, have subject get off Biodex  
16. Survey subject for any complaints of discomfort and answer any remaining questions  

Steps for Retest  
1. Reacquaint subject with testing procedures  
2. Have subject ride Fitron for 5 minutes at moderate pace  
3. Adjust Biodex chair and lever arm to same position as in testing  
4. Seat subject on Biodex and stabilize with strapping  
5. Set range of motion for 0 to 90 degrees of knee motion  
6. Set Biodex on passive mode and start Biodex lever arm at 60 degrees per second  
7. Follow same sequence as the testing session