The relationship between muscle length, integrated electromyographic activity, and torque of the biceps femoris muscle was investigated while the line of action of the muscle at the knee was held constant. Muscle length was changed by varying the hip joint angle. Sixteen subjects produced 1) maximal isometric contractions, 2) contractions with constant submaximal torque, and 3) contractions with constant submaximal muscle activity at four different hip positions (0, 45, 90, and 135 degrees of flexion). Simultaneous readings of hip angle, muscle torque, and raw and integrated electromyographic activity revealed that changes in muscle length influence production of integrated muscle activity and development of torque differently. During maximal isometric contraction, an increase in integrated electromyographic activity and a decrease in torque occurred as the muscle was shortened; the opposite occurred when the muscle was at lengthened positions. A greater difference in this relationship was noted when the respective electromyographic activity and torque were held constant. Some clinical questions were raised.

Key Words: Muscle contraction, Exercise test, Exertion.

The amount of torque produced by a muscle depends on the number of motor units activated, the muscle length, and the moment arm of the muscle. These variables have been studied in various combinations, but we could find no study that investigated the relationship among torque, EMG activity, and muscle length while the muscle’s moment arm was constant.

Results of previous studies have demonstrated that a direct linear relationship exists between muscle length and force of isometric contraction. The relationship between muscle length and force of isometric contraction has been ascribed by Morrison to two factors: 1) the muscle’s active contractile components and 2) the muscle’s passive elastic components.

Controversy exists concerning the EMG activity and muscle length relationship. Liberson and associates reported a drop in muscle activity as a muscle shortens. In contrast, Inman and associates and Miwa and Tanaka found an increase in EMG activity in the shortened muscle. Libet and associates reported the electrical activity of the human gastrocnemius muscle to be greatest at the intermediate muscle length and minimal at both the lengthened and shortened states.

Several investigators have demonstrated a direct relationship between integrated EMG and muscle force during isometric contractions within the range of the physiological muscle length; that is, at a given muscle length, the increase in developed muscle force parallels an increase in EMG activity.

Changes in the moment arm of a muscle appear to affect the development of recorded isometric torque and the production of EMG activity differently. Theoretically, as the moment arm of the muscle increases, the recorded torque produced increases, whereas the EMG activity decreases.

The controversy and validity of all of the previously cited studies may be related to the moment arm of the muscle. These studies investigated the length-force and the EMG-length relationships of the muscle by varying the distal joint position. This maneuver changed the moment arm of the muscle and introduced an uncontrolled variable.
The specific purpose of the present study was to examine the relationship between integrated EMG activity, torque, and length of the human biceps femoris muscle during isometric contraction while the knee joint angle remained constant. Changes in muscle length were produced by changes in hip joint angle.

METHOD

The long head of the biceps femoris muscle was selected for study. Similar functioning of the semimembranosus, semitendinosus, and the long head of the biceps femoris muscles has been demonstrated by EMG analysis. \(^6\)

Subjects

Twelve women and four men, 21 to 30 years of age, were recruited from the students and staff of the Division of Physical Therapy at the University of North Carolina at Chapel Hill. Each subject was shown the equipment, and the testing procedure was explained before subject preparation began.

Instrumentation

Torque measurements were provided by a force dynamometer incorporated within the Cybex II System.* Muscle force produced was directly related to torque developed because the internal mechanics remained constant at the knee joint. The EMG activity was processed by telemeter EMG equipment designed and constructed by the Biomedical Engineering Department of the University of North Carolina School of Medicine. The frequency response of the amplifier was 10 Hz to 10 kHz. The raw EMG was processed through an integrator with an integration period of 0.5 second and also through a linear envelope detector. Calibration of the system was verified for each recording session for each subject.

Surface electrodes were used to monitor the EMG activity, inasmuch as Bouisset and Maton demonstrated that surface electrodes provide a valid representation of superficial muscles when compared with fine-wire or needle electrodes. \(^12\)

Procedure

The belly of the long head of the right biceps femoris muscle was identified by palpation during a

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* Lumex, Inc, 100 Spence St, Bay Shore, NY 11706.
moderate contraction of the right knee flexor muscles. The skin was abraded, reducing resistance to below 20 K ohms DC. Then 16 mm, silver-silver chloride Beckman† surface electrodes were affixed longitudinally 1 cm apart over the belly of the long head of the right biceps femoris muscle. A manual muscle test was performed to ensure proper electrode placement.

To standardize the body position and localize the contraction of the proper muscle group, measures were taken to stabilize the body parts. The subject was seated on a chair with an adjustable back rest and an anterior cross bar to support the trunk in the various test positions. To prevent hip flexion during contraction, the right thigh was secured to the seat. The right knee was flexed to 60 degrees and the leg was attached to the lever arm of the Cybex II isokinetic exercise device. The lever arm axis was aligned with the knee joint and the speed adjustment was set at zero radians/second to provide an immovable resistance to knee flexion (Figure). The subjects were asked to produce three maximal contractions to become familiar with the apparatus before testing began.

The three phases of the testing procedure consisted of three brief isometric contractions of the hamstring muscle group at four different positions of hip flexion: 1) hip flexed to 135 degrees (leaning forward), 2) hip flexed to 90 degrees (sitting upright), 3) hip flexed to 45 degrees (leaning back), and 4) 0 degrees of hip flexion (supine). Each subject received one-minute relaxation periods between each contraction and three-minute periods between each phase of the experiment.

In the first phase of the study, the subject was asked to produce three maximal, three-second, isometric contractions of the hamstring muscle group at each of the four hip flexion positions. The position sequence was varied among subjects to rule out any learning effect. Simultaneous recordings of knee flexor torque as well as integrated and raw EMG data were recorded by a Model 906 C Honeywell Visicorder.‡

The second phase of the study required that the torque produced by the hamstring muscle group be constant for all test positions. One channel of a dual-channel oscilloscope was used to monitor the subjects' torque output level; the second channel was set at the torque level that represented the subject's lowest maximum muscle contraction effort for the four test positions as determined in phase one. For all the subjects this level proved to be the torque produced in the supine position.

During subsequent isometric contraction trials at 45, 90, and 135 degrees of hip flexion, the subject was asked to produce the torque level on the second channel that would equal that which had been established on the first channel. The oscilloscope thus provided a visual feedback system that enabled the subject to duplicate his initial torque output in the supine position during the remaining isometric contraction trials.

The third-phase procedure required that the EMG activity level of the biceps femoris muscle be constant for all test positions. The level chosen was the lowest maximum average EMG that had been produced in the first phase. For all subjects this proved to be the EMG activity level produced in the 135-degree hip position. The visual feedback level was set at this value. The subject was asked to meet, but not exceed, this EMG level during subsequent isometric contractions of the hamstring muscles in the positions of 90, 45, and 0 degrees of hip flexion.

Phases two and three provided a means by which each subject could generate constant hamstring muscle torque or constant EMG activity during isometric contractions of the hamstring muscle group at different muscle lengths. Performance of the second and third phases was alternated among subjects to rule

<table>
<thead>
<tr>
<th>Amount of Hip Flexion (degrees)</th>
<th>Anthropometric Measurements (cm)</th>
<th>Difference (cm)(^a)</th>
<th>Roentgenographic Measurements (cm)</th>
<th>Difference (cm)(^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>107.4</td>
<td>3.6</td>
<td>107.2</td>
<td>3.6</td>
</tr>
<tr>
<td>45</td>
<td>111.0</td>
<td>12.2</td>
<td>111.3</td>
<td>9.7</td>
</tr>
<tr>
<td>90</td>
<td>123.2</td>
<td>8.1</td>
<td>120.9</td>
<td>9.1</td>
</tr>
<tr>
<td>135</td>
<td>131.3</td>
<td></td>
<td>130.1</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Comparison between the two methods, \(r = .99\).
\(^b\) Difference between anthropometric measurements in different positions.
\(^c\) Difference between roentgenographic measurements in different positions.

† Beckman Instruments, Inc, Schiller Park, IL 60176.
‡ Honeywell, Test Instrument Division, Denver, CO 80217.

TABLE 1
Comparison of Measurements of Biceps Femoris Length from One Subject\(^a\)

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out any learning effect. In the second and third phases, simultaneous EMG activity and torque recordings were made as in the first phase of the study.

The total change in length of the long head of the biceps femoris muscle from the supine (shortened) position through the 135-degree hip flexion (lengthened) position was previously determined by Morrison\(^1\) and confirmed by an anthropometric and soft-tissue roentgenogram pilot study performed with the assistance of the Department of Radiology, North Carolina Memorial Hospital. Analysis of variance and Duncan's multiple-range mean comparison were used to determine the significance of the four testing situations.

**RESULTS**

Measurements from the origin to the insertion of the biceps femoris muscle were taken directly from a subject and from roentgenograms as the subject assumed the four test positions. Comparison of the values from the two methods of measurement revealed a correlation of .99. Measurements from the subject are shown in Table 1.

The change in length of the muscle was not constant with the change in angle of the hip joint. Only a small change in muscle length occurred between 0 degrees of hip flexion and 45 degrees of hip flexion. A much greater change took place between the angles of 45 to 90 degrees and 90 to 135 degrees.

Table 2 shows that no significant differences occurred between the muscle activity produced at 0-degree, 45-degree, and 90-degree positions of the hip during maximum muscle contraction. The integrated EMG activity at the 135-degree position was not significantly different from that at the 90-degree positions, but was significantly \((p < .05)\) less than that at the 0-degree and 45-degree positions.

Table 3 shows no significant difference in torque between the hip flexion positions of 45 degrees, 90 degrees, and 135 degrees during maximum muscle contraction. Also, no difference in torque was found between the 0-degree and 45-degree hip positions. Significantly less torque, however, was developed at the 0-degree hip position than at the 90-degree and 135-degree hip positions.

Biceps femoris muscle activity was monitored electromyographically while the subjects tried to keep the torque developed at a constant submaximal level. Table 4 shows the mean comparison of the integrated EMG activity as the subjects were placed in the four positions of hip flexion. More EMG activity was necessary for the subjects to develop the same torque with the hip flexed at 0 degrees than for any of the other hip-flexion positions. A significant \((p < .05)\) difference in biceps femoris EMG activity was also noted between the hip positions of 45 and 135 degrees. No significant differences were found in EMG activity between the 45-degree and 90-degree positions and the 90-degree and 135-degree positions. In general, more EMG activity was needed to maintain the same torque when the hip was flexed to a lesser degree.

The torque developed was recorded for the four different flexion positions as the subjects maintained a constant level of EMG activity in the biceps femoris muscle. A comparison of the means of the torque values is shown in Table 5. Significant \((p < .05)\) differences of torque occurred for the different hip-flexion positions except between 0 and 45 degrees. With the EMG activity held constant, the greater the degree of hip flexion, the greater the amount of torque.

**DISCUSSION**

The results of this study indicated that, with the moment arm of muscle held constant, 1) EMG activity of the biceps femoris muscle decreases as the muscle is lengthened and 2) the muscle develops a greater amount of torque in the lengthened state than in the shortened position. In both cases a greater difference was noted when the respective torque and integrated EMG activity were held constant than during maximal contraction.

When the subject attempted to produce a maximal muscle contraction at each hip position, no significant difference in integrated EMG activity was noted until the most lengthened muscle position was attained. In this instance, the EMG activity dropped significantly

<table>
<thead>
<tr>
<th>Positions</th>
<th>Mean Comparison of Biceps Femoris Muscle Activity at Various Hip-Flexion Positions as Subjects Produced Maximal Effort ((F = 3.26))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>1,952 mV/sec</td>
</tr>
<tr>
<td>45°</td>
<td>1,804 mV/sec</td>
</tr>
<tr>
<td>90°</td>
<td>1,547 mV/sec</td>
</tr>
<tr>
<td>135°</td>
<td>750 mV/sec</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Positions</th>
<th>Mean Comparison of Torque Developed by the Knee Flexor Muscles at Various Hip Flexion Positions as Subjects Produced Maximal Effort ((F = 3.73))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>38.7 N-m(^*)</td>
</tr>
<tr>
<td>45°</td>
<td>49.3 N-m</td>
</tr>
<tr>
<td>90°</td>
<td>57.3 N-m</td>
</tr>
<tr>
<td>135°</td>
<td>64.5 N-m</td>
</tr>
</tbody>
</table>

\(^*\) Newton-meters.
from the first two shortened muscle positions (Tab. 2).

Similar results were obtained when torque at each hip position was compared as the subject attempted to produce a maximal muscle contraction. In this case, however, the three angle positions providing a greater muscle length were not significantly different, but the first position (shortened muscle length) developed significantly less force than did the two lengthened muscle positions (Tab. 3).

These results differ from those obtained by Vredenbregt and Rau and Komi, who found that for maximal contractions at different muscle lengths, the values of EMG activity were the same. A procedural difference that changed the mechanics of the distal joint may account for this discrepancy. These authors changed the length of the muscle by changing the distal joint angle, which changed the moment arm of the muscle. In our study, the distal joint angle was held constant.

When the subject produced a constant submaximal torque at the four different test positions, the EMG activity decreased. Thus, fewer motor units may have been needed to maintain the same force when the muscle was in a lengthened position.

When the subject was asked to contract the hamstring muscle group at each position, with the muscle producing a constant submaximal EMG activity, the muscle group was able to maintain a greater force isometrically in the lengthened position. During this situation the torque produced showed a greater difference among the different test positions than the torque produced during maximal effort (Tabs. 3, 5).

**TABLE 4**

<table>
<thead>
<tr>
<th>Positions</th>
<th>Mean Comparison of Biceps Femoris Muscle Activity at Various Positions of Hip Flexion as the Subjects Developed a Constant Submaximal Torque (F = 11.56)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>1,827 mV/sec</td>
</tr>
<tr>
<td>45°</td>
<td>1,059 mV/sec</td>
</tr>
<tr>
<td>90°</td>
<td>580 mV/sec</td>
</tr>
<tr>
<td>135°</td>
<td>170 mV/sec</td>
</tr>
</tbody>
</table>

**TABLE 5**

<table>
<thead>
<tr>
<th>Positions</th>
<th>Mean Comparison of Torque Developed at Various Positions of Hip Flexion as the Subjects Maintained Constant Level of Muscle Activity from the Biceps Femoris (F = 42.5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>19.1 N·m²</td>
</tr>
<tr>
<td>45°</td>
<td>24.4 N·m</td>
</tr>
<tr>
<td>90°</td>
<td>34.3 N·m</td>
</tr>
<tr>
<td>135°</td>
<td>60.2 N·m</td>
</tr>
</tbody>
</table>

* Newton-meters.

This result differs from that reported by Haffajee and associates, who found that the average torque differs little between maximum contraction and EMG activity held constant.

The major factors affecting these results may be related to the anatomical make-up of the muscle, that is, parallel elastic components, contractile components, and innervation from Golgi tendon organs.

As a muscle is lengthened, the parallel elastic components are placed on stretch. These fibers may act like an elastic band that passively produces increased force with stretch. As the overall muscle force remains constant (torque constant), an increase in the force produced by this passive muscle component allows for a decrease in force developed by the contractile elements. Hence, fewer motor units are needed, which results in reduced EMG activity. The resetting of the spindle afferents may influence decreased motor unit firing; however, this probably does not account for the same torque. The balance between passive and active elements seems to be the major factor.

Another factor that may be involved is the placement of the muscle fiber crossbridges. The force developed by the active contractile elements of the muscle is governed by the relative position of the actin and myosin filaments of each sarcomere. A most efficient length of the muscle fiber seems to exist; that is, there seems to be a length at which the ratio between muscle force and EMG activity is greatest. The position of greatest muscle fiber efficiency appears to be the greatest length a muscle can obtain in situ. Thus, shortening the muscle decreases the efficiency of the muscle fiber.

Some studies have proposed that the change in EMG activity at different muscle lengths may be a result of autogenic inhibitory afferent innervation from Golgi tendon organs. These studies indicated that when the tendons are at a lengthened position, the inhibitory afferent impulses in the region of the tendon decreases autogenic muscle activity. The neuromuscular effect of decreasing the EMG activity at greater muscle length, together with the mechanical effect of increased force by the passive parallel elastic components, may account for the constant force and decrease in EMG activity of the lengthened muscle. More than one factor appears to be involved in production of EMG activity at different muscle lengths when the torque developed remains constant.

The results of our study concerning the EMG-length relationship are in general agreement with those of Inman and associates and Miwa and associates. The Liberson and associates' study found an increase of electrical activity in the gastrocnemius muscle as the muscle was placed in a shortened position, but a decrease in biceps brachii, triceps...
brachii, and deltoid muscle electrical activity as the muscle was shortened.\(^4\) Our results were not in agreement with the latter trend. By changing muscle length without altering the moment arm of the muscle, we found that the biceps femoris muscle in shortened length produced significantly greater EMG activity. Various parts of our study controlled for the effects of mechanical advantage and torque and eliminated these complicating factors.

The EMG activity produced and the torque developed did not change in a linear fashion (Tab. 2). With a constant difference in hip joint angle, a linear change might be expected. As noted from results of the muscle length variation pilot study, however, biceps femoris muscle length does not change in a linear fashion with the angle of hip flexion. The nonsignificant change in torque when the EMG activity was constant may reflect this anatomical factor.

**CLINICAL IMPLICATIONS**

The practical significance of the results offer some interesting alternatives to traditional hamstring muscle rehabilitation techniques and strength training. Our length-force results are in general agreement with those discussed earlier.\(^1\)–\(^5\) Currier\(^2\) and Felder\(^3\) advocate training the hamstring muscles in a position of greatest muscle length, thus allowing for maximum torque development. Our results indicate, however, that this maximal force level is accompanied by less integrated EMG activity than at other positions.

The question then arises, Is the desired training effect of the hamstring muscles accomplished through exercise in the lengthened position, where the greatest force is developed, or in the shortened position, which elicits far greater EMG activity? Could hamstring muscle strengthening following knee surgery be best accomplished with the patient supine on the exercise table rather than in the upright seated position? The seated position would allow the muscle to produce greater torque; however, the supine position would cause a greater activity of the muscle while simultaneously allowing for minimal force development, thus minimizing postsurgical pain and the danger of suture tear or soft tissue damage. More research is needed in this area to enable the clinician to answer such questions more intelligently.

**REFERENCES**