Neuromuscular Activation in Conventional Therapeutic Exercises and Heavy Resistance Exercises: Implications for Rehabilitation

Background and Purpose. Central activation failure and muscular atrophy are common after knee joint injury. Thus, exercises that aim to stimulate muscular hypertrophy and increase neural drive to the muscle fibers should be used during rehabilitation. This study examined the level of knee joint neuromuscular activation during 4 conventional therapeutic exercises (quadriceps femoris muscle setting, manual lateralization of the patella, rhythmic stabilization, and the pelvic bridging exercise) and 4 heavy resistance exercises (free-weight squat with a barbell, horizontal seated leg press, isolated knee extension with a cam mechanism, and isolated hamstring muscle curl) in young, untrained men who were healthy. Subjects. Thirteen male subjects (mean age = 25.3 years, SD = 3.0) with no previous history of knee injury participated in the study. Methods. Neuromuscular activation during the exercises was defined as the root-mean-square (RMS) electromyographic (EMG) signal normalized to the peak RMS EMG signal of a maximal isometric muscle contraction. Results. Low levels of neuromuscular activation were found during all conventional exercises (<35%). A limitation may be that only a few of many different conventional exercises were investigated. The highest level of neuromuscular activation (67%–79%) was observed during the open kinetic chain resistance exercises (isolated knee extension and hamstring muscle curl). None of the conventional exercises or heavy resistance exercises were found to preferentially activate the vastus medialis muscle over the vastus lateralis muscle. Discussion and Conclusion. The results indicate that heavy resistance exercises should be included in rehabilitation programs to induce sufficient levels of neuromuscular activation to stimulate muscle growth and strength. [Andersen LL, Magnusson SP, Nielsen M, et al. Neuromuscular activation in conventional therapeutic exercises and heavy resistance exercises: implications for rehabilitation. Phys Ther. 2006;86:683–697.]

Key Words: Electromyography, Neuromuscular activation, Neural drive, Physical therapy, Rehabilitation, Resistance exercise, Strength, Training.

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Knee joint injuries frequently occur in a range of sports. A major problem in relation to injury is the subsequent muscle wasting and loss of muscle strength (force-generating capacity of muscle) in both young and elderly people. Disuse atrophy of the quadriceps femoris muscle after injury is frequently associated with chronic knee joint instability, and persistent muscle atrophy has been reported after serious knee joint injury (eg, anterior cruciate ligament [ACL] rupture and subsequent reconstruction). Central activation failure also has been reported after knee joint injury. Furthermore, maximal muscle strength has been shown to be positively correlated to function during daily living tasks (eg, stair climbing) after ACL surgery. Thus, a major goal of knee joint rehabilitation is to enhance neuromuscular activation as well as stimulate muscle hypertrophy and thereby increase muscle strength.

More than half a century ago, DeLorme and colleagues recommended the use of heavy resistance training during rehabilitation following muscle and joint injury. Heavy resistance exercise induces relatively high levels of neuromuscular activation, which over a prolonged training period yields muscle hypertrophy, gains in muscle strength, and enhanced neural drive to the muscle fibers. Despite these findings, traditional physical therapy commonly rehabilitates the muscles and joints using "functional exercises," static contractions against no external resistance or dynamic contractions with a fixed load (eg, the weight of the body). Few studies have compared the effectiveness of traditional physical rehabilitation paradigms versus heavy resistance exercise. A recent study showed that heavy resistance training, in contrast to traditional physical therapy, increased muscle mass, maximal muscle strength, and neural drive in elderly individuals recovering from long-term muscle disuse and hip surgery.

A key factor in muscle strength progression is the "intensity" of exercise, which can be defined as a given percentage of the maximal muscle contraction strength. Electromyography (EMG) often is used as an indicator of intensity of exercise. A positive linear relationship between isometric muscle force and surface EMG amplitude has been documented previously. In addition, during dynamic muscle contraction, a positive proportionate relationship exists between muscle force and EMG amplitude, although this relationship may be slightly curvilinear in some muscles. Despite the inherent variance associated with measurements of EMG activity, it is generally agreed that normalization of the EMG amplitude with respect to the maximal EMG amplitude obtained during isometric conditions increases the reliability of the measurements. Thus, normalized EMG amplitude expressed as a percentage of the maximal EMG amplitude provides an approximate estimate of exercise intensity. Normalized EMG amplitude often is referred to as "the level of neuromuscular activation."

Strength adaptations have been observed in training studies where the intensity ranged between 40% and 95% of maximal intensity (for a review, see Fry), although it is generally agreed that intensities of at least 60% should be used for effective gains to occur. Thus, for a given exercise, it would be reasonable to assume that the level of neuromuscular activation should be at least in the range of 40% to 60% to stimulate muscle strength adaptations. Furthermore, it appears that a dose-response relationship exists between intensity of exercise and rate of muscle strength adaptations (ie, training at...
higher levels of neuromuscular activation yields greater strength gains).\textsuperscript{35-47} It can be hypothesized that, due to the relatively low external load, the level of neuromuscular activation during conventional therapeutic exercises lies below the adaptive threshold of 40\% to 60\% needed to stimulate gains in muscle strength and size. The aim of the present study was to investigate the level of knee joint neuromuscular activation with EMG during conventional therapeutic exercises versus typical heavy resistance exercises.

**Method**

**Subjects**

Thirteen young male subjects (mean age=25.3 years, SD=3.0; mean height=181 cm, SD=4; mean weight=75.8 kg, SD=6.2) with no previous history of knee injury participated in the study. None of the subjects had previously participated in regular resistance training of the lower extremities. All subjects gave written informed consent to participate in the study.

**Conventional Exercises**

Four exercises were examined: (1) quadriceps femoris muscle setting (Fig. 1, upper left), (2) manual lateralization of the patella (Fig. 1, upper right), (3) rhythmic stabilization (Fig. 1, lower left), and (4) the pelvic bridging exercise (Fig. 1, lower right). These exercises are commonly used during rehabilitation for strengthening of the leg muscles and for proprioceptive training. All subjects were familiarized with the exercises during a visit to the laboratory before the start of the study. All exercises were instructed by the same physical therapist.

**Quadiceps femoris muscle setting.** This exercise involves isometric contraction at an extended knee joint position against no external resistance. Subjects were placed in a supine position with the knee and hip extended. A small sandbag was positioned under the knee. The subjects were instructed to contract the muscles of the thigh as intensively as possible. This static exercise is used to strengthen the quadriceps femoris muscle during the early phase of rehabilitation where the patient is incapable of performing dynamic exercises.\textsuperscript{48-50}

**Manual lateralization of patella.** With the subjects relaxing in a supine position with the knee and hip extended, the patella was displaced laterally by the therapist using the largest possible pressure that did not cause discomfort in the knee. The subjects were
instructed to contract the quadriceps femoris muscle, and consequently patella moved medially (i.e., back to the neutral position). The exercise is thought to preferentially activate and strengthen the vastus medialis (VM) muscle, although this clinical belief lacks scientific documentation.

**Rhythmic stabilization.** Subjects were in an upright position with one leg flexed and the foot rested on a box. The knee joint angle was approximately 60 to 70 degrees. The examiner placed his hands above and below the subjects’ knee joint and encouraged the subjects to hold the leg in the same position, while manually applying moderate pressure in a rhythmic fashion from various angles to the distal and proximal parts of the thigh and lower leg, respectively. This exercise is a proprioceptive neuromuscular facilitation technique that is used to enhance proprioception and stability of the knee joint through facilitated coactivation of the muscles of the knee joint. Rhythmic stabilization is a common rehabilitation technique that can be applied to various joints and muscle groups.51

**The pelvic bridging exercise.** Subjects were placed in a supine position on the floor with the hip and knee joint flexed (anatomical joint angles of ~45° and 100°–110°, respectively) and plantar pedis on the floor. The subjects were instructed to lift the pelvis upward to full hip extension, and subsequently lower the body again. The exercise was executed unilaterally to maximize the load on the hamstring and gluteus muscles. Range of motion of the knee joint was approximately 20 degrees. The exercise is believed to strengthen and rehabilitate the hamstring and gluteus muscles, and is commonly used for patients with hip and knee injuries.52

**Heavy Resistance Exercises**

Four resistance exercises were examined: (1) free-weight squat with a barbell (Fig. 2, upper left), (2) horizontal seated leg press (Fig. 2, upper right), (3) isolated knee extension with a cam mechanism (Fig. 2, lower left), and (4) isolated hamstring muscle curl (Fig. 2, lower right).

**Free-weight squats with a barbell.** Subjects were standing upright with a barbell resting on the muscles of the neck just below the vertebral prominens. The subjects descended in a controlled manner by flexing the knee and hip simultaneously to a knee joint angle of approximately 100 degrees and a hip joint angle of approximately 90 degrees and subsequently rose in a similar fashion.

**Horizontal seated leg press (Technogym Isotonic Line*).** Subjects were seated horizontally with straight legs and 45 degrees of hip flexion. The subjects bent the leg (knee and hip joints) simultaneously to a knee joint angle of approximately 100 degrees and subsequently extended the leg in a similar fashion.

**Isolated knee extension with a cam mechanism (Technogym Isotonic Line).** Subjects were seated upright with the resistance pad resting on the tibia approximately 2 cm above the medial malleolus. The starting position was a knee joint angle of approximately 100 degrees. The subjects extended the knee in a controlled manner and subsequently flexed the knee back to the starting position.

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*Technogym USA Corp, 850 Fourth Ave S, Suite 300, Seattle, WA 98134.*
Isolated hamstring muscle curl (ie, knee flexion) with a cam mechanism (Technogym Isotonic Line). Subjects were lying in a prone position with straight legs and 10 degrees of hip flexion. The resistance pad was resting on the lower leg about 10 cm above the insertion of the Achilles tendon. The subjects flexed the knee to a knee joint angle of approximately 100 degrees and subsequently lowered the weight again. The hip joint angle was kept constant throughout the entire range of motion.

These exercises are commonly used in resistance training by both novice and experienced individuals. The first 2 resistance exercises are aimed primarily at the quadriceps femoris and gluteus muscles, the third exercise is aimed primarily at the quadriceps femoris muscle, and the fourth exercise is aimed primarily at the hamstring muscles. The heaviest weight that could be lifted 10 times in a controlled manner without a break (ie, 10-repetition maximum [RM]) was determined for each exercise during 3 familiarization visits to the labo-
Figure 4.
A typical recording of knee joint position and raw electromyographic activity during 1 set of 5 repetitions of the squat exercise. The ascending and descending parts of the position curve (bottom) represent the eccentric and concentric phases, respectively, of the exercise. GM=gluteus maximus muscle, ST=semitendinosus muscle, BF=biceps femoris caput longus muscle, RF=rectus femoris muscle, VM=vastus medialis muscle, VL=vastus lateralis muscle.
In all repetition exercises, the range of motion was from full knee extension to a knee joint angle of approximately 100 degrees.

Electromyography and Goniometry

The skin was shaved with a hand razor and carefully cleaned with ethanol before electrode placement. Bipolar surface EMG electrodes (Medicotest M400S) with a 2.5-cm inter-electrode distance were placed on the medial portion of the vastus lateralis (VL), VM, and rectus femoris (RF) muscles of the quadriceps femoris muscle approximately 15, 13, and 20 cm above the proximal border of the patella, respectively; on the biceps femoris caput longus (BF) and semitendinosus (ST) muscles of the hamstring muscle approximately 20 cm from the fossa poplitea; and finally on the middle of the gluteus maximus (GM) muscle. The EMG electrodes were connected directly to small preamplifiers and led through shielded wires to a differential instrumentation amplifier with a bandwidth of 10 to 1,000 Hz and a common mode rejection ratio better than 115 dB (Octopus AMT-8 EMG system). Aagaard et al previously documented that, with this experimental set-up, the amount of EMG crosstalk is negligible (<2%–6%).

Knee joint position was measured with a flexible electrogoniometer, which was positioned laterally over the right knee joint. Calibration of the goniometer signal was performed at anatomical knee joint angles of 0 and 90 degrees using a geometric retractor.

The EMG and goniometer position signals were sampled synchronously at 1,000 Hz and entered into a portable computer using an external A/D converter (DT-9804). A sampling frequency of 1,000 Hz for surface EMG was used in numerous previous studies, because most of the surface EMG signal is concentrated in the band between 20 and 200 Hz, and only negligible content occurs beyond 500 Hz. Surface EMG mean power frequency during maximal muscle contraction of the respective muscles (VL, VM, RF, ST, and BF) has been shown to be in the range of 70 to 115 Hz.

Maximal Voluntary Isometric Contraction

Peak EMG amplitude was recorded during maximal voluntary isometric contractions (MVICs) performed for the knee extensor muscles (at 10° and 90°), knee flexor muscles (at 10° and 90°), and hip extensor muscles (at 0° and 90°). Two maximal trials of each exercise were performed at the beginning of the test round, and 2 maximal trials of each exercise were performed at the end of the test round. For each muscle, the peak EMG amplitudes recorded at 10 and 90 degrees were not significantly different. In addition, the pre- and post-exercise peak EMG amplitudes were not significantly different. Therefore, to reduce the inherent variance of the recorded signal, the peak EMG amplitudes were averaged across the 2 joint angles and the pre- and post-exercise recordings for each muscle. This average...
peak EMG value was used for the EMG normalization procedure (see “Off-line Signal Processing” section).

Exercise Protocol
On the day of testing, the subjects warmed up on a Monark bicycle ergometer* at 100 W for 10 minutes. Two MVICs of the knee extensor, knee flexor, and hip extensor muscles were performed to obtain maximal EMG signal amplitude. Then 3 rounds of the following exercises were performed in a cyclic manner: squat, isolated knee extension, leg press, hamstring muscle curl, the pelvic bridging exercise, quadriceps femoris muscle setting, manual lateralization of the patella, and rhythmic stabilization. Four minutes of rest was allowed between exercises to avoid fatigue. During the resistance exercises, 5 repetitions with a predetermined 10-RM load were performed. During the pelvic bridging exercise, 5 repetitions with the load of the body were performed. During the quadriceps femoris muscle setting exercise, 5 isometric contractions of 3 to 4 seconds were performed. During manual lateralization of the patella, 5 repetitions were performed. During rhythmic stabilization, pressure was applied for 15 seconds above and below the knee from different angles. At the end of the third round of tests, 2 MVICs of the knee extensor, knee flexor, and hip extensor muscles were performed again.

Off-line Signal Processing
During the subsequent process of off-line analysis, the goniometer position signal was digitally low-pass filtered at a cutoff frequency of 10 Hz using a fourth-order zero-phase-lag Butterworth filter. All raw EMG signals were digitally high-pass filtered at a cutoff frequency of 5 Hz using a fourth-order zero-phase-lag Butterworth filter. Subsequently, the EMG signal was processed by a symmetric moving root-mean-square (RMS) filter with a time constant of 50 milliseconds. The RMS EMG signal was averaged in 10-degree knee joint angle intervals (ie. 10°–20°, 20°–30°, ..., 90°–100°) for the concentric phase of the dynamic exercises (squat, leg press, knee extension, hamstring muscle curl, and the pelvic bridging exercise), and averaged over a 1-second period around the peak RMS EMG amplitudes for the isometric exercises (quadriceps femoris muscle setting, manual lateralization of patella, and rhythmic stabilization). To reduce the variability of the signal obtained, the RMS EMG amplitudes were averaged over the 5 repetitions and 3 sets for each exercise (ie, total of 15 contractions). Finally, average RMS EMG amplitudes during the exercises were normalized relative to the isometric peak RMS EMG signal. The term “neuromuscular activation” refers to the normalized RMS EMG amplitudes.

Data Analysis
An analysis of variance with a subsequent Bonferroni corrected post hoc test was used to answer the question of whether normalized RMS EMG amplitudes differed between the exercises. Values are reported as mean ± standard error unless otherwise stated. P<.05 was accepted as significant.
Figure 7.

Quadiceps femoris muscle electromyographic (EMG) activity: rectus femoris. Quadiceps femoris muscle EMG activity was highest during isolated knee extension. The EMG activity decreased gradually during more extended knee joint positions. Relatively low levels of quadiceps femoris muscle neuromuscular activation were observed during the conventional exercises. Quadiceps femoris muscle setting produced the highest level of EMG activity among the conventional exercises. RMS=root-mean-square, ISO=isometric "quadiceps femoris muscle setting," KNE=isolated knee extension, LEG=leg press, MAN=manual lateralization of the patella, RYT=rhythmic stabilization, SQU=squat.

Results

Typical recordings of raw EMG activity and goniometer position signals are given in Figs. 3 and 4. Normalized RMS EMG values throughout the entire range of motion are presented in Figs. 5 to 10, and average values for range of motion of 10 to 100 degrees are presented in Tables 1 through 3. Generally, EMG activity was markedly higher during the resistance exercises compared with the conventional exercises (Tabs. 1–3). Normalized RMS EMG amplitudes were between 9% and 34% during the conventional exercises and between 12% and 86% during the resistance exercises when the total range of motion was considered (Figs. 5–10).

The VL, VM, and RF of the quadiceps femoris muscle demonstrated similar EMG patterns. Quadiceps femoris muscle EMG activity was greatest during isolated knee extension (Figs. 5–7), with normalized RMS EMG amplitudes of 68% to 74% (Tab. 1). Between exercises, quadiceps femoris muscle EMG amplitudes ranked as follows: isolated knee extension > leg press > squat > quadiceps femoris muscle setting > manual lateralization of the patella > rhythmic stabilization (Tab. 1). Quadiceps femoris muscle EMG amplitudes decreased markedly during gradual extension of the knee in the squat and leg press exercises (Figs. 5–7). None of the exercises selectively activated the VM muscle more than the VL muscle (Tab. 1), which also was evidenced by the fact that the VM/VL EMG ratio did not significantly exceed 1.00 at any knee joint angle or in any exercise (Fig. 8).

Hamstring muscle EMG was highest during isolated hamstring muscle curl (Figs. 9 and 10), with normalized RMS EMG amplitudes of 67% to 70% (Tab. 2). Antagonist coactivation of the hamstring muscles during squat and leg press exercises yielded similar EMG values (19%–40%) compared with the pelvic bridging exercise (24%–34%) where the hamstring muscles acted as agonists (Tab. 2). Between exercises, hamstring muscle (BF) EMG amplitudes ranked as follows: isolated hamstring muscle curl > the pelvic bridging exercise, leg press, squat > isolated knee extension > quadiceps femoris muscle setting > rhythmic stabilization (Tab. 2). Gluteus maximus muscle EMG activity was higher in squat and leg press exercises (55%–60%) compared with the pelvic bridging exercise (36%) (Tab. 3). Training loads lifted in the squat, leg press, isolated knee extension, and hamstring muscle curl exercises were 73±13 (X±SD) kg (range=60–95 kg), 240±39 kg (range=145–280 kg), 68±18 kg (range=35–100 kg), and 48±9 kg (range=35–60 kg), respectively.

Discussion and Conclusions

This study examined the level of neuromuscular activation during typical therapeutic exercises and heavy resistance exercises. A central dogma in conventional physical therapy is to strengthen the target muscles using functional exercises. The therapeutic exercises that we examined in this study (Fig. 1) are widely used within physical therapy to strengthen the muscles of the knee joint and are considered essential during rehabilitation following injury. In light of this, the central finding of our study was that relatively low levels of neuromuscular activation were observed in all of the conventional
No preferential activation of vastus medialis muscle (VM) over vastus lateralis muscle (VL) was seen in any exercise or during any knee joint range of motion because the VM/VL electromyographic activity ratio did not significantly exceed 1.00. ISO = isometric “quadriceps femoris muscle setting,” KNE = isolated knee extension, LEG = leg press, MAN = manual lateralization of the patella, SQU = squat.

exercises (Figs. 5–10). Below, the aspect of neuromuscular activation is discussed in relation to the potential benefits and limitations of these exercises.

**Quadriceps Femoris Muscle Neuromuscular Activation**

Central activation failure and persistent quadriceps femoris muscle atrophy have been reported after certain types of knee joint injury.\(^6^\)–\(^8^\) Thus, a major goal of rehabilitation should be to stimulate neuromuscular activation and enhance muscle growth. The quadriceps femoris muscle setting exercise (Fig. 1) is a widely used isometric exercise during the early phase of rehabilitation when the patient is incapable of performing dynamic exercises.\(^4^\)–\(^6^\) Although this specific exercise induced the greatest magnitude of quadriceps femoris muscle neuromuscular activation of the 4 conventional exercises examined (32%, 30%, and 24% for the VL, VM, and RF, respectively), the neuromuscular activation was below the threshold of 40% to 60% to induce significant hypertrophy and strength gains over a prolonged period of training. Furthermore, isometric exercises may not optimally stimulate strength adaptations.\(^6^\)–\(^9^\) Nevertheless, the quadriceps femoris muscle setting exercise may be helpful to lessen muscle wasting during phases of joint immobilization where dynamic exercises are rendered impossible. The low magnitude of neuromuscular activation during manual lateralization of patella and rhythmic stabilization exercises (8%–17%, Tab. 1) indicates that these exercises are not efficient in strengthening the quadriceps femoris muscle. It can be speculated, however, that such exercises may have merit in proprioceptive training.\(^5^\)

Among the resistance exercises, overall quadriceps femoris muscle EMG activity was highest during isolated knee extension (Figs. 5–7). In contrast, Escamilla et al.\(^1^\) reported that, in experienced weight lifters, quadriceps femoris muscle EMG activity was higher in squat and leg press exercises compared with isolated knee extension at more flexed knee joint positions, although EMG activity was highest during isolated knee extension at more extended positions. The discrepancy between the present and previous results may be related to the training status of the subjects (ie, novice versus experienced subjects). The role of task learning and improved intermuscular coordination plays a major role in strength development during the initial weeks of training, especially when complex exercises are used.\(^6^\) The isolated knee extension exercise is a simple single-joint movement, whereas the squat and leg press exercises are more functional and complex multijoint movements, which may explain the higher neuromuscular activation in isolated knee extension in novice subjects (Figs. 5–7). Thus, a combination of simple and complex exercises probably should be used during rehabilitation to optimally stimulate maximal muscle strength and hypertrophy and to improve postural balance and intermuscular coordination.

**Safety Aspects**

The safety aspects of heavy resistance exercise in relation to rehabilitation also should be considered. A concern regarding isolated knee extension has been that this type of exercise imposes greater stress on the ACL compared with the squat and leg press exercises, especially in more extended knee joint positions.\(^1^\)–\(^3^\) However, neither isolated knee extension nor any other type of controlled
Figure 9.
Hamstring muscle electromyographic (EMG) activity: biceps femoris caput longus. Hamstring muscle EMG activity was highest during isolated hamstring muscle curl exercise. Relatively low levels of hamstring muscle neuromuscular activation were observed during the conventional exercises. RMS=root-mean-square, ISO=isometric "quadriceps femoris muscle setting," HAM=hamstring muscles, PEL=pelvic bridging exercise, RYT=rhythmic stabilization.

heavy resistance exercise produces higher compressive or tensile forces on the structures of the knee joint compared with many activities of daily living. Moreover, the results of a recent resistance training study suggest that, after ACL surgery, maximal muscle contractions are not associated with anterior knee pain. To our knowledge, no previous researchers have reported serious knee joint injuries specifically due to heavy resistance exercise. Furthermore, resistance training is associated with a very low incidence of injury compared with other types of training. Thus, considering the high level of neuromuscular activation as well as its simplicity, the isolated knee extension exercise appears to be highly efficient during rehabilitation. The relatively high level of quadriceps femoris muscle neuromuscular activation during the flexed knee joint position of the leg press and squat exercises (Figs. 5-7), combined with a high degree of functionality, indicates that these exercises also could be included in the rehabilitation from knee joint injury.

Preferential VM Neuromuscular Activation
It is a common clinical observation that the VM appears to be more profoundly atrophied than the other components of the quadriceps femoris muscle after injury. Although in many instances this observation may be a visual artifact, there may be cases where the VM needs specific strengthening. The VM acts as an antagonist to the VL in aligning the patella relative to the line of pull of the quadriceps femoris muscle. Thus, weakening of the VM may increase the tendency of the patella to migrate laterally. A number of exercises have been suggested to strengthen the VM preferentially.

Manual lateralization of the patella (Fig. 1) has been widely used during rehabilitation to preferentially activate and strengthen the VM muscle. In the present study, the use of this exercise to preferentially activate the VM over the VL was not substantiated because the VL and VM showed similar levels of neuromuscular activation (17% and 16% respectively, Tab. 1). Likewise, other types of knee joint exercises do not seem to produce a preferential activation of the VM over VL, which is supported by the present results (Tab. 1). Some studies have indicated greater VM activation in the terminal phase of knee extension, whereas Gryzlo et al reported no preferential activation in this phase of motion. In the present study, no indications of preferential VM recruitment were observed near full extension of the knee joint, as evidenced by the fact that the VM/VL ratio of EMG values did not exceed 1.00 in any knee joint position or in any exercise (Fig. 8). It should be noted, however, that preferential activation of the VM over the VL can be obtained with myoelectrical stimulation.

Hamstring Muscle Neuromuscular Activation
A high level of hamstring muscle strength has been suggested to provide potential protection of the knee joint in athletes who are healthy as well as in patients with ACL injuries. Hamstring muscle coactivation during forceful knee extension reduces the anterior shear of the tibia relative to the femur, thereby reducing the tensile stress on the ACL. The purpose of the pelvic bridging exercise is to strengthen and rehabilitate the hamstring and gluteus muscles, and this exercise is often used during rehabilitation for patients with knee or hip
Figure 10.
Hamstring muscle electromyographic (EMG) activity: semitendinosus. Hamstring muscle EMG activity was highest during isolated hamstring muscle curl exercise. Relatively low levels of hamstring muscle neuromuscular activation were observed during the conventional exercises. RMS=root-mean-square, ISO=isometric "quadriceps femoris muscle setting," HAM=hamstring muscles, PEL=pelvic bridging exercise, RYT=rhythmic stabilization.

Table 1.
Normalized Root-Mean-Square Electromyography Values in Descending Order for the Vastus Lateralis (VL), Vastus Medialis (VM), and Rectus Femoris (RF) Muscles (Average Values±Standard Error Throughout the 10°–100° Range of Motion)∗

<table>
<thead>
<tr>
<th></th>
<th>VL</th>
<th>VM</th>
<th>RF</th>
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<tbody>
<tr>
<td>KNE</td>
<td>74%±15%</td>
<td>79%±25%</td>
<td>68%±9%</td>
</tr>
<tr>
<td>LEG</td>
<td>53%±13%</td>
<td>54%±8%</td>
<td>39%±13%</td>
</tr>
<tr>
<td>SQU</td>
<td>43%±11%</td>
<td>45%±10%</td>
<td>27%±9%</td>
</tr>
<tr>
<td>ISO</td>
<td>32%±11%</td>
<td>30%±11%</td>
<td>24%±7%</td>
</tr>
<tr>
<td>MAN</td>
<td>17%±7%</td>
<td>16%±6%</td>
<td>12%±4%</td>
</tr>
<tr>
<td>RYT</td>
<td>10%±5%</td>
<td>9%±4%</td>
<td>8%±3%</td>
</tr>
<tr>
<td>HAM</td>
<td>9%±6%</td>
<td>9%±6%</td>
<td>8%±5%</td>
</tr>
<tr>
<td>PEL</td>
<td>6%±4%</td>
<td>6%±4%</td>
<td>5%±4%</td>
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</table>

∗Dotted separation lines indicate significant difference between exercises (P<.05). HAM=isolated hamstring muscle curl, ISO=isometric "quadriceps femoris muscle setting," KNE=isolated knee extension, LEG=leg press, MAN=manual lateralization of the patella, PEL=pelvic bridging exercise, RYT=rhythmic stabilization, SQU=squat.

The relatively low level of neuromuscular activation for the BF (34%), ST (24%), and GM (36%) in the pelvic bridging exercise suggests that this exercise does not effectively stimulate muscle strength gains. In comparison, antagonist coactivation of the hamstring muscles during the squat and leg press exercises produced similar EMG amplitudes compared with that of the pelvic bridging exercise where the hamstring muscles acted as agonists (Tab. 2). Hamstring muscle neuromuscular activation was found to be highest during the isolated hamstring muscle curl exercise. Thus, the isolated hamstring muscle curl exercise appears to be the most efficient exercise to strengthen the hamstring muscles in novice subjects. Furthermore, during the hamstring muscle curl exercise, a very homogenous level of BF and ST neuromuscular activation was observed (70% and 67%, respectively), in contrast to a more differential BF and ST activation pattern during the other exercises (Tab. 2). In agreement with previous findings, a preferential recruitment of the BF over the ST was observed during the leg press, squat, and isolated knee extension exercises (Tab. 2) where the hamstring muscles act as an antagonist to the quadriceps femoris muscle. A preferential BF recruitment also has been observed during isolated knee extension performed in an isokinetic dynamometer and has been speculated to be a protective effect to avoid excessive medial rotation of the tibia, which imposes stress on the ACL during forceful quadriceps femoris muscle contraction.

A limitation of this study may be that uninjured subjects were used. Thus, a deficit in neuromuscular activation may be expected in injured individuals compared with uninjured individuals. However, this deficit would likely vary among various injury conditions, making it difficult to achieve any meaningful comparison among different types of knee joint injuries. Future studies should be conducted to investigate the effectiveness of these exercises in relation to various injury conditions. A strength of this study was that non–resistance-trained subjects were used. Thus, the results may well relate to injured individuals because most people who undergo rehabilitation are novices with regard to resistance training. Thus, we conclude that the conventional exercises used in this study produce levels of neuromuscular
Table 2.
Normalized Root-Mean-Square Electromyography Values in Descending Order for the Biceps Femoris Caput Longus (BF) and Semitendinosus (ST) Muscles (Average Values±Standard Error Throughout the 10°–100° Range of Motion)*

<table>
<thead>
<tr>
<th>Muscle</th>
<th>BF</th>
<th>ST</th>
</tr>
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<tbody>
<tr>
<td>HAM</td>
<td>70%±14%</td>
<td>67%±13%</td>
</tr>
<tr>
<td>LEG</td>
<td>40%±17%</td>
<td>22%±9%</td>
</tr>
<tr>
<td>PEL</td>
<td>34%±14%</td>
<td>24%±6%</td>
</tr>
<tr>
<td>SQU</td>
<td>35%±14%</td>
<td>19%±6%</td>
</tr>
<tr>
<td>KNE</td>
<td>23%±13%</td>
<td>9%±4%</td>
</tr>
<tr>
<td>ISO</td>
<td>17%±13%</td>
<td>12%±11%</td>
</tr>
<tr>
<td>RYT</td>
<td>11%±5%</td>
<td>11%±6%</td>
</tr>
<tr>
<td>MAN</td>
<td>12%±7%</td>
<td>9%±6%</td>
</tr>
</tbody>
</table>

* Dotted separation lines indicate significant difference between exercises (P<.05). HAM=isolated hamstring muscle curl, ISO=isometric "quadriceps femoris muscle setting," KNE=isolated knee extension, LEG=leg press, MAN=manual lateralization of the patella, PEL=pelvic bridging exercise, RYT=rythmic stabilization, SQU=squat.

Table 3.
Normalized Root-Mean-Square Electromyography Values in Descending Order for the Gluteus Maximus Muscle (Average Values±Standard Error Throughout the 10°–100° Range of Motion)*

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Value ± Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEG</td>
<td>60%±16%</td>
</tr>
<tr>
<td>SQU</td>
<td>55%±14%</td>
</tr>
<tr>
<td>PEL</td>
<td>36%±12%</td>
</tr>
<tr>
<td>HAM</td>
<td>28%±14%</td>
</tr>
<tr>
<td>ISO</td>
<td>27%±14%</td>
</tr>
<tr>
<td>MAN</td>
<td>20%±16%</td>
</tr>
<tr>
<td>KNE</td>
<td>18%±10%</td>
</tr>
<tr>
<td>RYT</td>
<td>11%±9%</td>
</tr>
</tbody>
</table>

* Dotted separation lines indicate significant difference between exercises (P<.05). HAM=isolated hamstring muscle curl, ISO=isometric "quadriceps femoris muscle setting," KNE=isolated knee extension, LEG=leg press, MAN=manual lateralization of the patella, PEL=pelvic bridging exercise, RYT=rythmic stabilization, SQU=squat.

activation that are below the threshold of 40% to 60% to effectively stimulate muscle strength gains. It should be recognized, however, that only a few of many different conventional exercises were investigated and that more challenging and intense exercises may yield higher levels of neuromuscular activation. The open kinetic chain resistance exercises (isolated knee extension and hamstring muscle curl) produced the highest levels of neuromuscular activation in novice subjects. The closed kinetic chain resistance exercises (squat and leg press) also produced relatively high levels of neuromuscular activation in the flexed knee joint position. Based on the present results, therefore, we recommend the use of controlled heavy resistance exercise as a supplement to the traditional physical therapy regimens used in knee injury rehabilitation to induce sufficient levels of neuromuscular activation and thereby stimulate muscle growth and strength.

References


