Electromyographic activity and applied load during seated quadriceps exercises

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ABSTRACT

MATHESON, J. W., T. W. KERNOZEK, D. C. W. FATER, and G. J. DAVIES. Electromyographic activity and applied load during seated quadriceps exercises. *Med. Sci. Sports Exerc.*, Vol. 33, No. 10, 2001, pp. 1713–1725. **Purpose:** The aim of this study was to quantify and compare mean quadriceps muscle activity and applied load for eight seated quadriceps exercises using four types of resistance. **Methods:** Using surface electromyography (EMG), the right rectus femoris (RF), vastus lateralis (VL), and vastus medialis oblique (VMO) muscles of 52 university students aged 23.5 ± 3.4 yr (35 female and 17 male subjects) were examined during the exercises. Resistance devices included an ankle weight (78 N), blue Thera-Band® tubing, a Cybex® 340 isokinetic dynamometer, and an Inertial Exercise Trainer® (IET). Electrogoniometer data were collected to determine the range of motion (ROM), angular velocity, and phase (concentric/eccentric) of exercise. Load cell data were analyzed to determine tubing and IET applied loads during exercise. A within-subjects criterion was used to improve intrasubject EMG reliability. All EMG values were normalized to a 100% maximum voluntary isometric contraction. Repeated measures ANOVAs with Bonferroni comparisons were used for statistical analysis. **Results:** Within-subject effects of muscle and exercise were significant ($P < 0.05$) for both the concentric and eccentric muscle activity. The interaction effect of mean average EMG amplitude across exercises for the concentric phases of knee extension was significant ($P = 0.001$). No significant interactions were found for the eccentric phases of all seated quadriceps exercises. None of the exercises selectively isolated the VMO over the VL; however, the VMO/VL ratio was less ($P < 0.05$) during the concentric phases of the free weight and elastic tubing exercise when compared with the others. Eccentric phase VMO/VL ratios revealed that inertial resistance elicited greater muscle activity than other forms of resistance exercise. **Conclusion:** These findings suggest clinicians should consider biomechanical and resistance data when developing a strengthening program for the quadriceps muscle. Some seated quadriceps exercises may be more appropriate for certain rehabilitation goals than others. **Key Words:** ELASTIC, IMPULSE, INERTIAL, VASTUS MEDIALIS OBLIQUE

When treating a client with a weakness of the quadriceps muscle, the clinician controls applied load, joint range of motion (ROM), and angular velocity in a progressive manner to restore strength. The applied load is largely dependent on the type of resistance selected. Free weights, elastic tubing, isokinetic dynamometers, and recently the Impulse Inertial Exercise Trainer® (IET) (Engineering Marketing Associates, Newnan, GA) are all types of resistance devices used in dynamic knee exercises (13). The majority of free-weight and weight machine exercises use isotonic resistance. In isotonic exercises, muscle length changes as a fixed resistance (barbell, weight plate) is moved throughout a ROM. The applied load is not constant because the length of the moment arm (resistance to joint center) changes throughout the ROM. Thus, the maximum resistance that can be moved is dependent on the amount of muscle force generated at the weakest point in the ROM. On the other hand, elastic resistance cannot be labeled as a form of isotonic resistance because of the inherent properties of the elastic material. Unlike sand-filled ankle weights or a barbell, the resistance generated by the latex or polymer elastic material varies according to its percent of elongation (stretch) during the exercise (17). An advantage of elastic resistance is that it does not rely on gravity to provide resistance. This increases its potential for use in more functional movement patterns such as overhead throwing motions (26). Elastic resistance devices have gained popularity in knee rehabilitation because of their low cost, simplicity, versatility, and portability. Several investigators have examined the efficacy of elastic tubing exercises in knee rehabilitation (15,22). None of these studies examined quadriceps muscle activity or the resistance properties of elastic resistance devices during seated quadriceps exercises.

In contrast to free weights and elastic tubing, which can be used both as part of a home program and in the clinic, isokinetic exercise is performed only in the clinical setting. Isokinetic exercise is characterized by "accommodating resistance." Accommodating resistance is the biomechanical principle that allows the muscle to be dynamically loaded to its maximum capability throughout the entire ROM. The use of isokinetic exercise in quadriceps muscle strengthening and testing has been well researched (8,18,20).

Inertial loading is a relatively new type of resistance developed on the basis of the principle of inertia. Inertia is defined as the resistance of an object to a change in motion. Inertial exercise requires the use of the IET device. The IET uses a weight-mounted sled that glides on a horizontal rail.

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Albert (2) has described IET inertial loading as "horizontal, submaximal, gravity eliminated plyometrics." On the basis of this description and its design, the IET machine has been used as a neuromuscular strengthening tool in rehabilitation to simulate the momentum and velocity changes of functional and recreational activities (13). At present, only a few investigations have examined the use of the IET as a strengthening tool (1,2,28,33). Furthermore, no published research on lower extremity inertial loading exists, nor have there been any studies comparing inertial loading to other types of resistance devices.

Along with a thorough knowledge of the type of resistance or load being applied, the clinician should have a good understanding of quadriceps muscle biomechanics during eccentric and concentric muscle actions. The quadriceps muscle, consisting of the rectus femoris (RF), vastus intermedius (VI), vastus medialis (VM), vastus medialis oblique (VMO), and vastus lateralis (VL), acts as one net force on the tibia via the patella and infrapatellar tendon. Normal alignment and function of the quadriceps muscle depend on a balance between the medial and lateral muscular components and passive structures that attach to the patella (9). With its insertion along the superior medial patella and its medially directed angle of pull, the VMO's role as a primary dynamic medial stabilizer of the patella has been well documented (21). Furthermore, imbalance of the relative medial and lateral vasti and rectus muscles is thought to be the cause for a number of patellofemoral tracking disorders (11). Most commonly, the patella tracks or is pulled too far laterally. Therefore, clinicians have proposed that an exercise that would selectively strengthen the VMO would be very beneficial in rehabilitation. Recent reviews of the literature (6,30) have demonstrated that this goal is likely unrealistic. However, several of these studies have demonstrated that certain knee exercises activate the quadriceps muscles to a larger degree than others. Clinicians, recognizing that quadriceps strengthening exercises often empirically improve clients' patella pain and symptoms, have hypothesized that perhaps just general strengthening of the quadriceps may strengthen the VMO to a "threshold level" where it can provide sufficient stabilization for proper patellar tracking without selective VMO activation (6,12). Further research is needed in this area to determine if quadriceps strengthening may be correlated with decreased patellar pain. In order to examine the issue of selective VMO activation in relation to composite quadriceps activity, the VMO/VL normalized electromyographic ratio is often used as a dependent research variable (6,12,19,32).

When prescribing quadriceps strengthening exercises, one should not rely solely on empirical evidence. Quadriceps strengthening exercises require biomechanical support and experimental quantification to be fully accepted. Therefore, the purpose of this study was to quantify and compare the EMG activity and applied load of eight seated quadriceps exercises using free-weight, elastic tubing, isokinetic, and inertial resistance. To compare the EMG activity of the eight exercises, two hypotheses were tested. The first hypothesis was that the differences in mean average EMG activity of RF, VL, or VMO muscles would not be dependent on the type of seated quadriceps exercise performed. The second hypothesis was that no significant differences in the VMO/VL ratios of mean average EMG activity would exist between the eight exercises in this healthy population.

MATERIALS AND METHODS

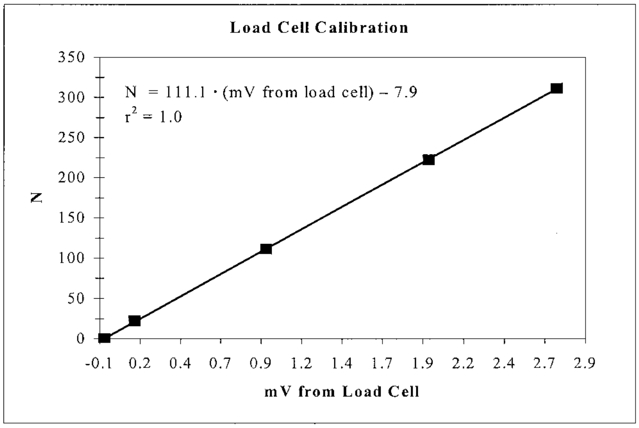
Subjects

Thirty-five female and 17 male subjects (23.5 ± 3.4 yr) from a university student population volunteered to participate in this study. Volunteers with a history of right knee surgery, a right lower extremity injury that required medical attention in the past year, or current knee pain were excluded from participation. Before enrollment in the study, all subjects were provided an explanation of the purpose, procedures, and potential risks and benefits of the study. In accordance with the requirements of the University of Wisconsin-La Crosse Institutional Review Board for the Protection of Human Subjects, all subjects provided their written informed consent before testing. All testing took place in the physical therapy program's biomechanics laboratory.

Instrumentation

EMG. Muscle activity data were collected with a Therapeutics Unlimited® Model 67 Multichannel EMG Amplifier/Processor Unit (Therapeutics Unlimited, Iowa City, IA) using bipolar silver/silver chloride disk surface electrodes (19 mm fixed interelectrode distance) interfaced with a desktop personal computer (PC). Each electrode had an on-site solid-state differential amplifier (gain, 35 ± 10%) embedded in a plastic enclosure. The common mode rejection ratio was 87 dB at 60 Hz, and the input impedance was greater than 15 MΩ at 100 Hz. The Therapeutics Unlimited® unit was capable of acquiring a 40- to 4000-Hz raw EMG signal and had additional gain settings of 500, 1000, 2000, 5000, and 10,000. The digital acquisition of data at 10,000 Hz was obtained with the use of a 16-bit analog-to-digital converter (RUN Technologies, Laguna Hills, CA) enclosed in a PC. This high sampling rate was thought necessary to acquire representative data during the high-velocity inertial exercises. All raw EMG data from the Therapeutics Unlimited® unit were collected and stored on a Pentium 133 MHz desktop PC with the use of custom software (Datapac III®, version 1.1, RUN Technologies).

Electrogoniometer. A Universal Self-Aligning Electrogoniometer (ULGN-67, Therapeutics Unlimited®) was used to measure knee ROM during the eight seated quadriceps exercises. The electrogoniometer consisted of a rotational potentiometer with a scale factor of 5.55 $mV \cdot degree^{-1}$ of rotation and resistive load of ± 1.0%. Two flexible plastic arms extended from the potentiometer. The electrogoniometer was centered over the subject's right lateral knee joint line with the two axes in line with the greater trochanter and lateral malleolus. Three Velcro® straps held the goniometer in place. Electrogoniometer data were collected simultaneously with the EMG data.



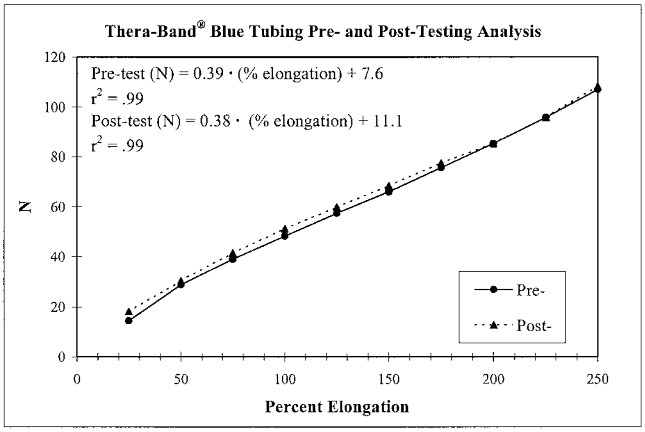


FIGURE 1—Calibration data for the load cell (*top*) and Thera-Band® blue tubing (*bottom*) with regression equations and regression line displayed.

Load cell. A Model 31 Load Cell Transducer and Universal Inline Amplifier (Sensotec, Columbus, OH) was used to measure the applied load during the elastic and inertial resistance exercises. The load cell had two threaded studs welded to either side of a central steel diaphragm that housed the transducer. Two large washers (0.95 cm) and one U-bolt (0.64 cm × 3.49 cm) were attached to each side of the transducer. This allowed placement of the transducer to be in series with either the nylon IET rope or elastic tubing. An 18-V power supply (J&B Equipment, Bloomington, MN) was used to power the amplifier, which provided an output voltage range of ±10 V at 2.5 mA. Calibration of the load cell occurred before data collection began. Certified weights in 2.25-kg, 4.5-kg, and 11.25-kg increments were placed in series with the load cell. A depiction of the calibration results are shown in Figure 1.

Cybex® 340 isokinetic dynamometer. The Cybex® 340 Isokinetic Rehabilitation and Testing System (Henley Healthcare, Inc., Sugar Land, TX) served three main purposes in this investigation. First, it acted to standardize positioning during six of the eight seated quadriceps exercises. Second, it served as the resistance for the three isokinetic exercises. Finally, the dynamometer acted as a testing instrument for the pre- and postmaximum voluntary isometric contraction (MVIC) trials. Before use in this experiment, the Cybex® 340 dynamometer was calibrated following the manufacturer's protocol. The intrasubject reliability of Cybex® series dynamometers has been described as good to excellent in the literature (3,18).

The isokinetic dynamometer used in this study provided only accommodating resistance in a passive mode. This meant that this dynamometer was only capable of providing a resistive force at the constant predetermined angular velocity. This limited the use of this dynamometer to concentric muscle activity only. Newer dynamometers, in addition to working in the passive mode, can work in an active mode to actively generate forces to resist joint movement. Thus, these newer dynamometers allow eccentric muscle activity (24). Only concentric isokinetic exercise was performed in this study; therefore, limitations existed when comparing this type of resistance to the others.

Elastic tubing. Thera-Band® blue tubing (The Hygenic Corp., Akron, OH) was used to provide elastic resistance for two of the eight seated quadriceps exercises. To be consistent with clinical use, a length of blue elastic tubing was prepared as described in the *Thera-Band® Lower Body Instruction Manual* (The Hygenic Corp.). This resulted in a looped piece of blue tubing 32 cm in diameter. This length was selected in an attempt to provide similar resistance to that of the ankle weight and IET sled load used in the study. A nonslip sailor's bowline knot was tied to keep the tubing ends together. In order to test the reliability and to determine the resistance properties of the elastic tubing, the procedure described by Page et al. (25) was used. Before the study began, the looped piece of tubing, in series with the load cell, was stretched in 25% increments to 250% of its original resting length. The average load cell values of five trials at each elongation percentage were calculated. This procedure was repeated once the experiment had been completed. Using statistical software (SPSS 8.0, SPSS, Inc., Chicago, IL), a bivariate linear regression analysis was performed on both data sets to determine linear prediction equations for the applied load (Fig. 1). These equations were similar to the regression equation for blue tubing calculated by Hughes et al. (17). Between pre- and posttesting, the tubing was stretched over 1100 times. Therefore, a dependent *t*-test was performed to examine if the pre- and posttest data were significantly different. A mean statistical difference (1.86 ± 1.2 N; $P < 0.001$; 95% CI, −2.72 to −1.00) between the pretest and posttest tubing data was found. Although this is a statistically significant difference, there may have been no practical differences between the data sets. A difference of 1 or 2 N during exercises that generated an average of 47 to 168 N of force was determined to be acceptable. Possible reasons for this statistical difference were knot slippage, tubing breakdown, and measurement error. In summary, these findings demonstrated that the Thera-Band® blue tubing continued to have a linear percent elongation to resistance relationship and had little change (<4%) in resistance over 1100 stretching events.

IET device. The IET device consisted of a platform sled on high-alloy steel wheels that glide horizontally along plastic tracks mounted on the guide rail. This IET sled/rail system was designed to have a very low coefficient of friction. Attached to the sled was an inelastic nylon rope. This rope, via pulleys and an ankle strap, allowed for the application of the inertial load to the user. When the user extended the knee against the rope, the sled moved along the rail until it encountered the center pulley. At this point, the direction of pull of the rope was reversed, and the user was subjected to a force from the rope equal to the inertia created by the concentrically generated acceleration of the sled (2).

Unlike the other quadriceps exercises examined, the IET exercises could not be performed from the Cybex® chair. In an attempt to standardize subject position during IET exercise, a standard metal straight back chair with wooden armrests was altered to the necessary specifications. A 1.3-cm-thick plywood board with a 1.0-cm-thick seat cushion was attached across the wooden armrests of the chair. A second piece of 1.3-cm plywood was used to extend the height of the chair back. The modified chair provided a seating surface that was 68 cm from the floor. This height was necessary to allow unrestricted ROM of the knee during the inertial exercise. An additional pad, if needed, was placed behind the subject's back to maintain 80° to 90° of hip flexion similar to the positioning provided by the Cybex® chair. An extra piece of webbing was added to the standard Thera-Band® ankle strap from medial to lateral, crossing the plantar surface of the foot, in order to prevent the main strap from sliding proximally during exercise. This modified strap was used in all elastic tubing and IET exercises.

Because of the large horizontal forces generated by the IET, it was possible for the IET to slide on the concrete laboratory floor. To prevent this movement, large sandbags were placed in front of and behind the legs of the modified chair (95 kg) and on the base of the IET (126 kg). This helped to ensure that the majority of force generated by the sled was transferred to the subject.

Testing Protocol

Orientation session. All 52 subjects attended a 1-h orientation session before testing. Subjects were required to attend the orientation session within 2 wk of testing (mean, 4.0 ± 2.7 d). During this orientation, subjects completed the informed consent form, received instruction in all exercise techniques, practiced all eight exercises, and performed several MVIC practice trials on the dynamometer. Requiring subjects to practice MVIC trials increases the likelihood of a true maximum being obtained during testing (31,34). The two IET exercises required the greatest amount of orientation. To standardize IET instruction, a specific "hands on" technique was used with all subjects (Impulse IET manual, Engineering Marketing Associates). During the large-arc IET exercise, each subject underwent 10 passive repetitions before independent practice. This involved manually moving the subject's leg through the ROM for 10 cycles. On the tenth repetition, the subject was asked to continue independently. Verbal feedback was given to correct exercise technique if necessary.

Testing session. testing began with the subject performing a 5-min warm-up on a cycle ergometer at a "comfortable" resistance. After the warm-up, the electrogoniometer, surface electrodes, and reference electrode were strapped to the subject's right lower extremity. Before placement of each surface electrode, the subject's skin was shaved, abraded with fine sandpaper, and cleaned with rubbing alcohol. An electrolytic paste (Parker Laboratories, Inc., Fairfield, NJ) was applied to the electrodes before attachment to the skin. Prefabricated double-sided adhesive tape was used to adhere the electrodes to the right quadriceps femoris in a method similar to that described by Delagi and Perotto (9). The RF electrode was placed over the RF muscle belly, halfway between the anterior superior iliac spine and superior border of the patella. The VL electrode was applied over the VL muscle belly, approximately 8 cm proximal to the lateral joint line of the knee. The VMO electrode was applied over the VMO muscle belly, approximately 4 cm proximal to the superior medial angle of the patella. A silver reference electrode was placed over the right tibial tuberosity. A second reference electrode was used to connect the dynamometer frame to the EMG unit. This ground electrode was necessary to remove electrical noise from the EMG signal when the subject was seated in the dynamometer chair. Finally, a gait belt was used to tether all cords to the subject's waist in order to avoid interference with the dynamometer arm or exercise equipment. Each subject performed several partial squats to ensure that the EMG equipment and electrogoniometer were functioning correctly.

After electrode placement, the subject was seated in the Cybex® chair. The subject was placed as far back in the chair as possible, and the three-point shoulder and lap belt was fastened. The dynamometer axis was aligned with the right lateral femoral epicondyle. The dynamometer arm was attached to the subject's lower leg with the bottom of the shin pad above the subject's medial malleolus. ROM stops were placed with the subject's knee in a fully extended position and then in 90° of flexion. Because of the location of the EMG surface electrodes, the dynamometer thigh strap was not used. This strap is often used to provide stabilization during isokinetic exercise by limiting the amount of substitute or supplemental motions that occur at the hip. This may be important at higher isokinetic velocities when the effects of inertia may cause the thigh to lift off of the dynamometer chair. In an attempt to control for this, all subjects were reminded to maintain posterior thigh contact with the chair seat during all isokinetic exercises. However, the inability to use the thigh strap was a limitation of this study.

After subject positioning, five MVIC trials with the dynamometer arm at 60° of knee extension were performed. The MVIC trials were necessary to establish a 100% EMG reference value for the EMG data collected throughout the study. Each MVIC trial lasted 6 s, with a 90-s rest interval between trials. This 90-s rest was selected to prevent fatigue (29). Strong verbal encouragement was given to each subject during all MVIC trials (5). After completion of all exercises, five post-MVIC trials were performed in a manner identical to the pre-MVIC trials. The purpose of the pre- and post-MVIC trials was to provide the necessary data to test the reliability of the acquired exercise EMG data (14).

Seated quadriceps exercises. After five pre-MVIC trials were completed, the subject completed the eight seated quadriceps exercises. The order of the free-weight, elastic tubing, isokinetic, and inertial resistance exercises was randomized to avoid an order effect of the exercises. However, the angular velocities within each type of resistance exercise were completed from slow to fast (i.e., $60°\cdot s^{-1}$ then $180°\cdot s^{-1}$). This may have been a limitation of this study but was necessary because of testing logistics.

Free-weight exercises were performed with the subject positioned and belted into the dynamometer chair. A 7.9-kg ankle weight was strapped to the subject's right ankle. Each subject performed the free-weight extension exercises in rhythm with a digital metronome set at 40 $beats\cdot min^{-1}$ (bpm). The subject was instructed to extend his or her knee through a full 90° arc of motion, hearing the metronome tone at full extension and again at 90° of flexion ($60°\cdot s^{-1}$).

Elastic tubing exercises were performed with the subject positioned and belted into the dynamometer chair. The looped piece of Thera-Band® blue tubing was connected in series to the load cell. The load cell was fixed to an eyebolt in the floor of the Cybex® frame underneath the seat. The slower tubing exercise was performed at $60°\cdot s^{-1}$ using the metronome in the manner described previously for the free-weight quadriceps exercise. The faster tubing exercise was performed with the metronome at 60 bpm ($180°\cdot s^{-1}$). The subject was instructed to perform a full 90° arc of knee flexion/extension reaching full extension (0°) with each beat of the metronome.

Isokinetic exercises were performed with the subject positioned as described for the MVIC trials. Each subject performed two sets of repetitions at each of the three isokinetic velocities ($60°\cdot s^{-1}$, $180°\cdot s^{-1}$, and $300°\cdot s^{-1}$). First, the subject was instructed to perform a progressive four-repetition warm-up at 25%, 50%, 75%, and 100% of maximal effort, respectively. These graded repetitions were followed by a 30-s rest period. The subject then performed six maximal knee extension/flexion repetitions. Data acquisition occurred during the second set of repetitions. An additional 30-s rest period was allowed between isokinetic velocities. During the isokinetic exercises, all subjects received visual feedback from the Cybex® monitor. The use of visual and verbal feedback during isokinetic exercise has been shown to have a positive effect on performance (5).

Impulse IET exercises consisted of the subject moving from the dynamometer chair to the IET chair. The subject was positioned with a rolled towel underneath the right knee. This was done to maintain consistency with the description of the seated quadriceps exercise found in the IET exercise manual. The IET rope was attached to the subject using the same ankle strap from the tubing exercises. Following recommendations from the IET manual, a sled load of 7.9 kg was used for all testing. On the basis of empirical evidence, this sled weight was thought to be appropriate for initial training sessions (2). Each subject performed two inertial loading exercises. The first, or large-arc exercise, began with the sled front edge positioned on the rail 67 cm from the center pulley. This limited the subject to an arc of approximately 60° of ROM. This is near the maximal amount of ROM allowed by the IET for the quadriceps exercise. A larger arc of motion would have required a longer guide rail for the sled. The second, or small-arc exercise, began with the sled front edge 42 cm from the center pulley. This limited the subject to approximately 30° of motion. By shortening the ROM, the duration of time the subject had to respond to the inertial changes was decreased. In both exercises, the predetermined sled position was maintained, and the chair was moved forward or backward until the IET rope and ankle strap were taut. This placed the subject's knee in approximately 90° to 110° flexion. This position was designated as the initial starting point (IP) of the inertial exercise ROM. The subject began the exercise by extending the knee against the rope. The sled accelerated along the rail until it passed the center pulley. When the sled was directly over the center pulley, the subject's leg was at the end of available extension ROM. This position was called the end-point (EP) of ROM. The EP occurred at the end of the acceleration or concentric portion of the exercise. After passing the center pulley, the angle of pull of the rope reversed, and inertia from the weighted sled continued down the rail with a force equal to the initial concentric acceleration. This occurred as the subject was returning (flexing) his or her leg to the IP. Therefore, during knee flexion the subject was required to decelerate the sled. This represented the eccentric portion of the inertial exercise. Therefore, acceleration of the sled began and deceleration of the sled ended at the IP in the ROM. Albert et al. (1) and Albert (2) have described two types of inertial exercise. The first, tonic exercise, is defined as the action of decelerating the sled from the EP to the IP while maintaining a constant rope tension. The second, phasic exercise, is defined as the action of creating slack in the rope and suddenly decelerating the sled in the ROM between EP and the IP. Phasic inertial loading exercises have the potential to produce significantly higher eccentric forces than tonic exercises. Only the tonic exercise was examined in this study. This was done because most subjects were unable to perform phasic exercise correctly in two sessions and the tonic exercise is the recommended inertial exercise to use during the initial stages of rehabilitation (2,33).

Data Collection

With the high sampling rate of 10,000 Hz, the computer hardware allowed a maximum recording of 20 s of exercise activity. Data acquisition began when the subject achieved the desired angular velocity and demonstrated smooth repetitious motion. The exception to this was during the isokinetic exercises, where all exercise repetitions were recorded. This resulted, depending on the exercise, in the acquisition of data for 6 to 15 cycles of knee flexion/extension.

Quadriceps EMG and electrogoniometer data were collected for all 10 MVIC trials and during the eight knee exercises. Load cell data were collected during the two elastic tubing and two inertial exercises. Using the custom software, all raw data were visually examined. Data containing poor signals, a high number of artifacts, or unexplained noise were excluded from processing. All remaining data were processed using a 60-Hz notch filter and root mean square (RMS) algorithm over a 15-ms moving window. An example of one subject's processed EMG, electrogoniometer, and load cell data for all eight exercises is shown in Figures 2, 3, and 4.

Reduction of EMG data. During testing, it was possible that electrodes had moved slightly, skin temperature had changed, EMG noise and crosstalk had increased, and/or the subjects had fatigued. Other factors that prevent representative EMG signal acquisition are listed in the literature (4,31,34). The method described by Hintermeister et al. (14) was used to assess whether the EMG data had remained consistent over the hour of testing. Data were excluded from further analysis if the mean posttest MVIC differed from the mean pretest MVIC by more than 2 standard deviations. Using this within-subject MVIC criterion, a large amount of EMG data were removed from the study. After this procedure, acceptable data remained for 28 subjects' RF muscles, 33 subjects' VL muscles, and 28 subjects' VMO muscles. A complete set of muscle data across all eight exercises remained for 16 subjects (10 female and 6 male subjects, age 24.4 ± 5.6 yr).

Selection of muscle activity data. Using the Datapac III® software and the electrogoniometer data, three to four contractions were selected for analysis. This involved visual examination of each trial and manually dividing each contraction into concentric and eccentric portions on the basis of electrogoniometer data. The concentric muscle action was separated from the eccentric muscle action by selecting the ROM data with a positive slope. Likewise, the eccentric muscle action was defined as the ROM data with a negative slope. Data collected when the goniometer was at full extension (slope = 0) was not included. A different method was used to divide the muscle activity into concentric and eccentric muscle actions for the isokinetic trials. Although isokinetic dynamometers theoretically function at a constant angular velocity, several limitations should be considered (7,24). Initially, the body segment exercised must accelerate to reach the preset angular velocity. Once the body segment reaches the desired angular velocity, velocity overshoot occurs as the dynamometer slows the body segment to the preset velocity. Therefore, true isokinetic exercise only occurs after the user has "caught" the dynamometer arm and been slowed to the preset angular velocity. One should also realize that as the preset isokinetic angular velocity increases, a greater knee extension ROM arc is required to match the dynamometer's preset angular velocity (7,8,24). In an attempt to obtain EMG activity during "true" isokinetic exercise, the selection of data occurred when the slope of the electrogoniometer signal was constant after the impact artifact from the body segment reaching the desired velocity. The electrogoniometer data were also analyzed to calculate the mean average duration of a set of contractions and the mean angular velocity during the seated quadriceps exercise.

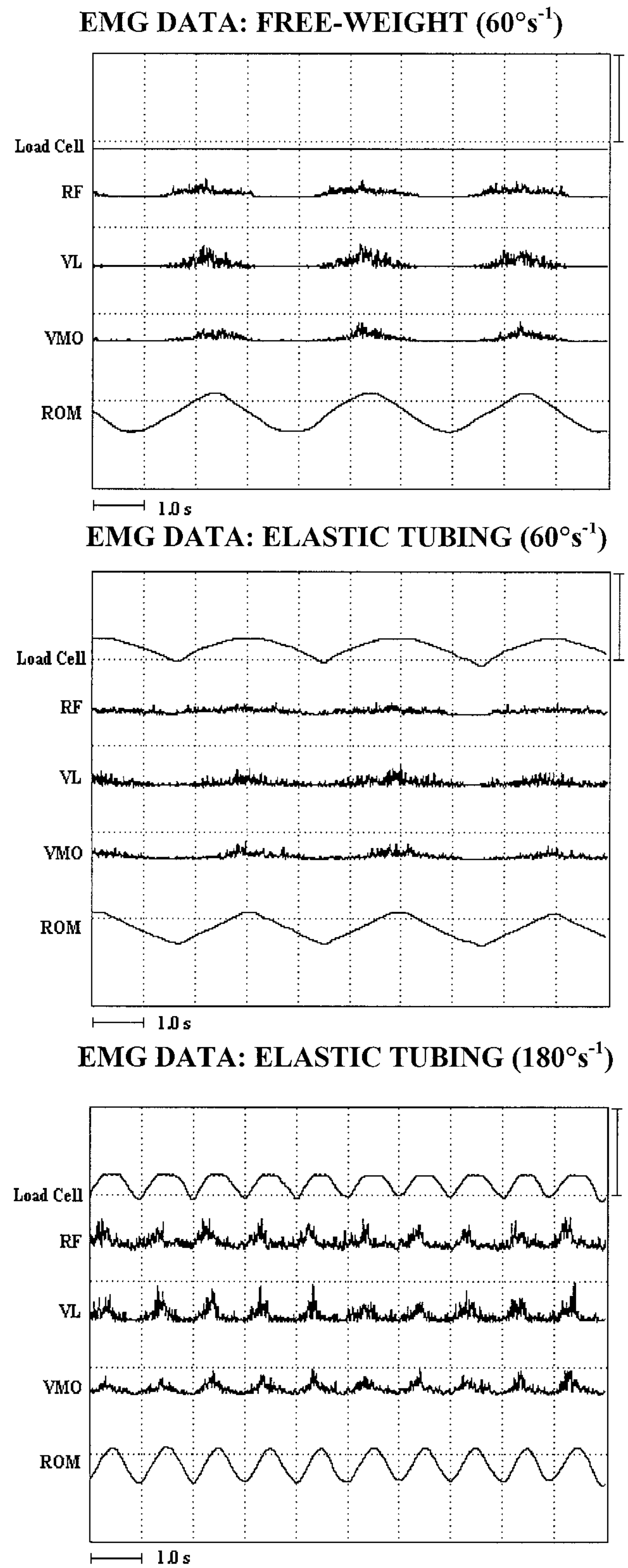


FIGURE 2—Processed load cell, EMG, and electrogoniometer data of one subject's free-weight and Thera-Band® elastic tubing seated quadriceps exercises.

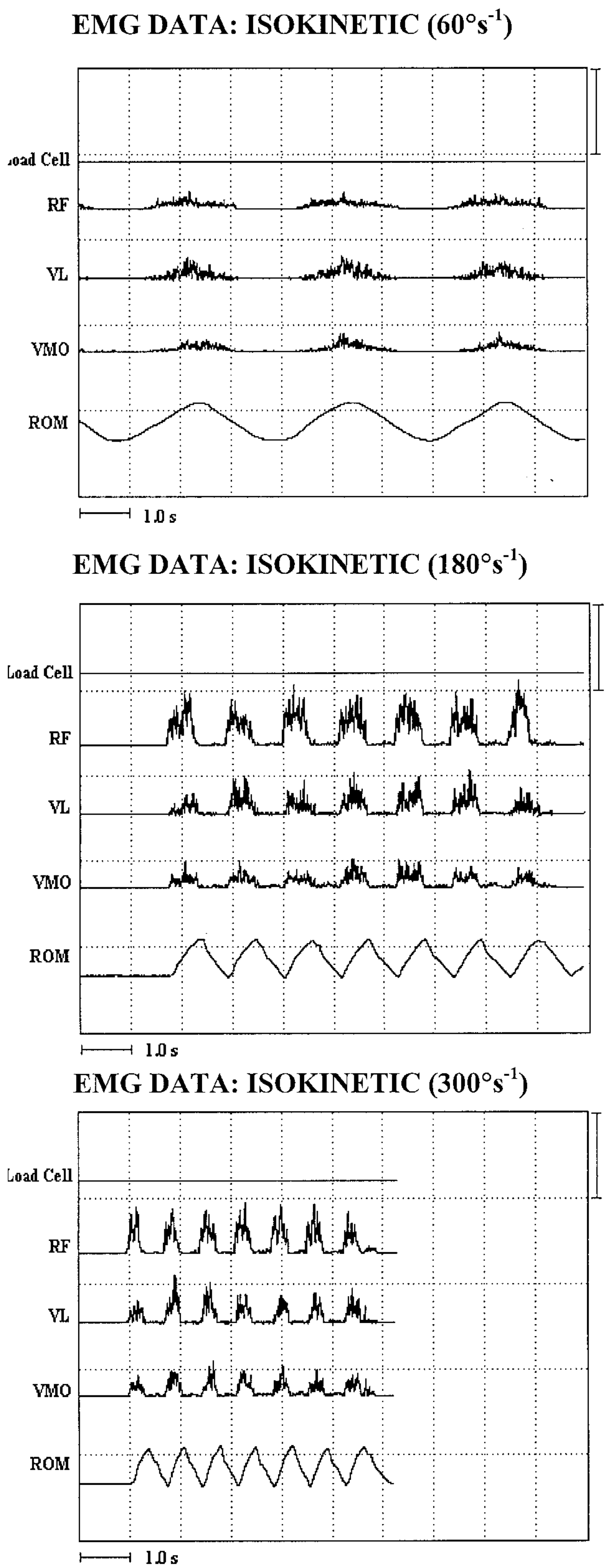


FIGURE 3—Processed load cell, EMG, and electrogoniometer data of one subject's isokinetic seated quadriceps exercises.

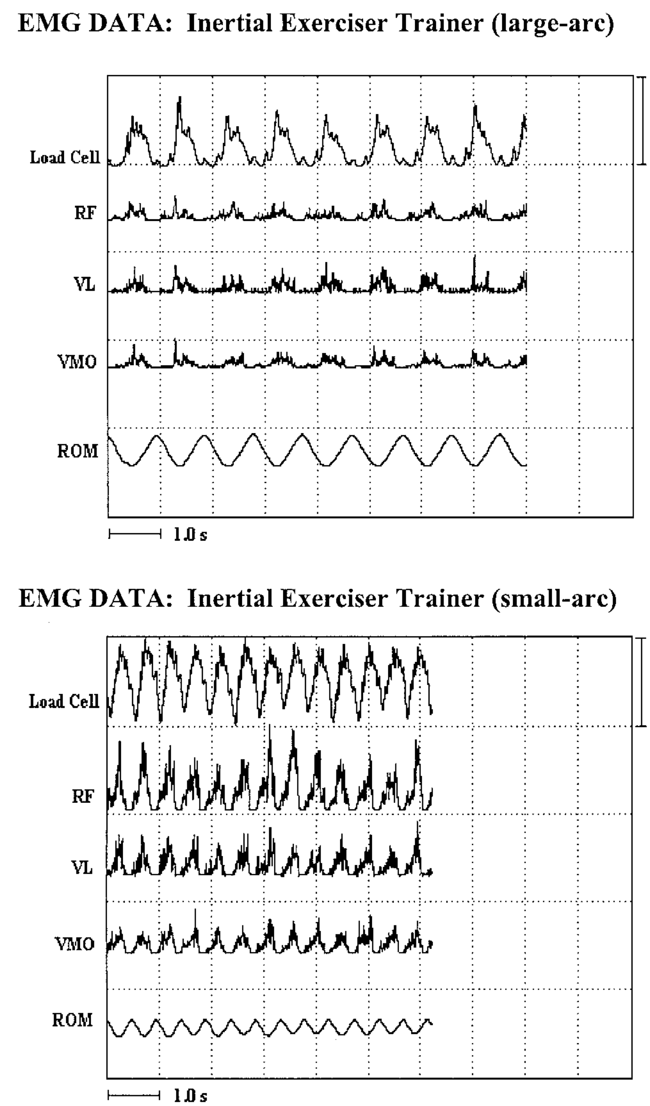


FIGURE 4—Processed load cell, EMG, and electrogoniometer data of one subject's Impulse IET seated quadriceps exercises.

Variables. Once the processed EMG activity for each set of contractions was selected, divided into eccentric and concentric phases, and stored on the computer, several calculations were performed. Mean average muscle phase duration (the mean of the average duration for each of the selected contractions), mean peak muscle action amplitude (the mean of the peak EMG value reached during the concentric or eccentric phase of the selected contractions), and mean average muscle action amplitude (the mean of the average EMG value reached during the concentric or eccentric phase of the selected contractions) were calculated from the processed EMG data. All values were normalized to the subject's MVIC. This value was selected using the maximum peak processed amplitude from the pre- or post-MVIC trials, depending on which was larger.

Peak and mean applied load across the eccentric and concentric portions of the tubing and IET exercises was analyzed using the load cell data. The conversion of load cell values (mV) to newtons was processed with the pretest calibration data.

Statistical Analysis

Only data from the 16 subjects containing complete sets of mean average EMG amplitude values across all eight

TABLE 1. Subject number (N) and means ± (SD) for range of motion (ROM), duration of muscle action (Δt), and angular velocity of the right lower extremity during the eight seated quadriceps exercises.

Exercise	N	Extension (Concentric Phase)			Flexion (Eccentric Phase)		
		ROM (°)	Δt (ms)	Velocity ($°\cdot s^{-1}$)	ROM (°)	Δt (ms)	Velocity[a] ($°\cdot s^{-1}$)
Free-weight ($60°\cdot s^{-1}$)	36	83.4 (8.9)	1286 (87)	73.7 (9.4)	83.1 (9.1)	1444 (83)	64.2 (8.9)
Elastic tubing ($60°\cdot s^{-1}$)	39	81.8 (8.8)	1258 (99)	71.1 (10.2)	80.7 (9.1)	1434 (109)	63.1 (8.9)
Elastic tubing ($180°\cdot s^{-1}$)	39	80.7 (7.8)	430 (40)	211.4 (21.5)	80.4 (7.4)	447 (49)	207.3 (31.3)
Isokinetic ($60°\cdot s^{-1}$)	40	69.3 (11.4)	1360 (203)	50.4 (7.2)	NA	NA	NA
Isokinetic ($180°\cdot s^{-1}$)	39	53.2 (12.4)	373 (65)	145.3 (18.9)	NA	NA	NA
Isokinetic ($300°\cdot s^{-1}$)	40	46.7 (16.3)	187 (47)	259.3 (63.4)	NA	NA	NA
Impulse IET (large arc)	39	61.7 (9.5)	374 (51)	187.5 (29.0)	62.7 (7.6)	412 (48.0)	178.1 (27.9)
Impulse IET (small arc)	36	31.2 (7.3)	216 (25.0)	165.9 (39.6)	31.2 (7.3)	231 (33.5)	149.9 (32.5)

NA, not applicable (ROM data not collected for flexion phase of isokinetic exercises).
[a] Eccentric angular velocities are negative; however, only absolute values are shown in this table.

exercises were statistically analyzed. Analysis was performed using a statistical software package (SPSS 8.0) and a Pentium III desktop computer. A 3 × 8 factorial design analysis of variance (ANOVA) with repeated measures across both factors (muscle, exercise) was used to examine the relative contributions of muscle recruitment and exercise selection on the mean average EMG values found during concentric muscle actions. A 3 × 5 factorial design ANOVA with repeated measures across both factors was used to examine the relative contributions of muscle recruitment and exercise selection to the mean average EMG results found during eccentric muscle activity. Separate one-way repeated measures ANOVAs were used to examine the effects of the normalized mean EMG ratio (VMO/VL) across either the concentric or eccentric muscle actions. In an attempt to reduce the type I error of the repeated measures ANOVAs, degrees of freedom were corrected using the Geisser-Greenhouse method when sphericity assumptions were not upheld (16). This study used *post hoc* Bonferroni procedures to examine any significant within-subject effects found by the ANOVAs. Finally, *post hoc* calculations of eta squared (η^2) and observed power were completed to assess the practical significance of the data (16).

RESULTS

Mean and standard deviation values for acceptable electrogoniometer data including ROM, duration of muscle activity, and angular velocity are displayed in Table 1. Results of ROM data for the three metronome-paced exercises (free-weight and tubing) demonstrated an 80.4° to 83.4° arc of motion during both knee extension and flexion. Results also confirmed that the inertial exercises were within ±3° of their desired ROM arcs, 60° and 30°, respectively. The portion of the isokinetic ROM arc where subjects exercised at a constant angular velocity decreased as the preset isokinetic angular velocity increased. The electrogoniometer data also demonstrated that eccentric muscle activity occurred at a slower angular velocity than concentric muscle activity for all five seated quadriceps exercises containing eccentric activity.

Mean and standard deviation values for the peak average and mean average applied load over the contraction phase are shown in Table 2. The free-weight and tubing exercises had peak average loads that differed by less than 5 N (0.5 kg). Inertial loading exercises demonstrated the greatest concentric and eccentric mean peak and average loads when compared with the tubing and free-weight quadriceps exercises.

TABLE 2. Subject number (N), duration of muscle action (Δt), and mean ± (SD) for the average and peak applied load during the free weight, Thera-Band® blue tubing, and Impulse IET seated quadriceps exercises.

Exercise	N	Concentric Phase Applied Load[a]			Eccentric Phase Applied Load		
		Δt (ms)	Average	Peak	Δt (ms)	Average	Peak
Free-weight ($60°\cdot s^{-1}$)	30	1283 (87)	NA	77	1444 (83)	NA	77
Elastic tubing ($60°\cdot s^{-1}$)	39	1258 (99)	48.1 (4.8)	73.7 (6.7)	1434 (109)	43.0 (5.7)	72.7 (5.7)
Elastic tubing ($180°\cdot s^{-1}$)	39	430 (40)	47.1 (5.3)	72.7 (7.5)	447 (49)	43.1 (4.8)	70.4 (11.8)
Impulse IET rope (large arc)	39	374 (51)	79.5 (19.4)	178 (41.3)	412 (48.0)	37.5 (11.1)	185 (64.0)
Impulse IET rope (small arc)	36	216 (25.0)	168 (40.7)	239 (58.9)	231 (33.5)	101 (26.4)	239 (103)

NA, not assessed.
[a] All average and peak load values are expressed in newtons.

TABLE 3. Subject number (N) and means ± (SD) for peak and average normalized EMG amplitude of the right quadriceps muscle during the eight seated quadricep exercises.

Knee Extension Exercise	Muscle	N	Peak EMG Amplitude[a] Concentric	Peak EMG Amplitude[a] Eccentric	Average EMG Amplitude Concentric	Average EMG Amplitude Eccentric
Free-weight (60°·s^{-1})	RF	27	29.9 (17.3)	17.9 (9.0)	7.1 (3.6)	4.4 (2.5)
	VL	32	40.5 (17.0)	25.1 (9.5)	10.2 (5.4)	7.5 (4.7)
	VMO	26	40.2 (18.9)	24.0 (12.9)	7.5 (3.2)	4.1 (1.7)
Elastic tubing (60°·s^{-1})	RF	27	27.7 (17.7)	18.3 (9.2)	7.0 (4.1)	4.3 (2.4)
	VL	31	41.4 (16.5)	27.1 (10.2)	11.0 (5.3)	8.4 (4.7)
	VMO	25	38.4 (16.6)	22.7 (10.4)	7.8 (3.3)	5.0 (2.4)
Elastic tubing (180°·s^{-1})	RF	27	38.3 (18.6)	21.5 (9.8)	12.6 (6.2)	6.2 (2.7)
	VL	31	51.8 (19.7)	25.0 (9.3)	17.2 (6.6)	8.8 (4.9)
	VMO	26	51.6 (18.7)	26.4 (10.8)	17.1 (5.9)	6.8 (2.7)
Isokinetic (60°·s^{-1})	RF	27	91.3 (17.6)	NA	34.0 (6.1)	NA
	VL	32	87.2 (17.0)	NA	29.9 (6.7)	NA
	VMO	26	90.6 (15.3)	NA	28.8 (5.7)	NA
Isokinetic (180°·s^{-1})	RF	27	79.1 (17.2)	NA	28.4 (7.0)	NA
	VL	31	74.7 (20.6)	NA	30.3 (9.0)	NA
	VMO	24	79.2 (21.8)	NA	30.5 (7.4)	NA
Isokinetic (300°·s^{-1})	RF	27	64.8 (14.8)	NA	21.6 (7.9)	NA
	VL	32	75.8 (21.0)	NA	28.2 (10.6)	NA
	VMO	26	71.8 (28.9)	NA	26.0 (9.2)	NA
Impulse IET (large arc)	RF	26	48.7 (23.2)	42.7 (21.4)	11.1 (6.5)	9.0 (4.7)
	VL	30	48.2 (25.2)	42.7 (19.8)	12.8 (5.3)	10.8 (5.1)
	VMO	26	55.7 (28.6)	50.0 (23.4)	13.2 (8.1)	10.0 (6.4)
Impulse IET (small arc)	RF	26	66.9 (30.4)	70.4 (26.3)	16.8 (9.0)	21.4 (9.4)
	VL	31	68.5 (28.0)	70.7 (33.0)	18.2 (8.9)	21.7 (9.0)
	VMO	24	75.3 (33.8)	78.6 (36.0)	17.8 (10.6)	23.8 (11.2)

RF, rectus femoris; VL, vastus lateralis; VMO, vastus medialis oblique; NA, not applicable (the isokinetic dynamometer was limited to concentric/concentric muscle activities).
[a] All values expressed as percentages of maximum voluntary isometric contraction.

The means and standard deviations for the average and peak EMG amplitude are listed in Table 3 for all eight seated quadriceps exercises. The greatest mean and peak EMG amplitudes occurred during the three isokinetic exercises. The free-weight and elastic tubing exercises at 60°·s^{-1} were nearly identical in peak and average amplitude, varying by less than ±2% over both the concentric and eccentric muscle activity. The small-arc IET exercise was the only exercise to demonstrate greater eccentric than concentric mean peak and average EMG activity.

Statistical testing of the mean average EMG activity that occurred in the concentric and eccentric phases of the seated quadriceps exercises revealed significant results. The two-way repeated measures ANOVA for the concentric portions of the eight extension exercises revealed significant ($P <$ 0.05) differences in the main effects of quadriceps muscle EMG activity and exercise selection across the eight seated quadriceps exercises. A significant interaction effect (muscle × exercise) was also found (P = 0.001, power = 0.99). This meant that quadriceps muscle recruitment was influenced by exercise selection. Therefore, further interpretation of the significant main effects was not performed. The repeated measures ANOVA for the eccentric muscle action data revealed significant main effects for eccentric exercise type (P = 0.001, power = 1.0) but not for muscle recruitment (P = 0.27, power = 0.66). No significant interaction effect was found for the eccentric portion of exercise contractions (P = 0.09, power = 0.50). Significant concentric interaction and nonsignificant eccentric interaction effects are shown in Figure 5.

The results of *post hoc* testing examining the interaction effect of concentric exercise on quadriceps muscle recruitment are shown in Table 4. None of the concentric phases of the eight knee exercises resulted in activation of the VMO over the VL. The RF muscle demonstrated the greatest variability in mean average muscle activity across the eight exercises. *Post hoc* testing examining muscle recruitment in the five eccentric portions of the extension exercises revealed that the VL had a significantly higher overall mean

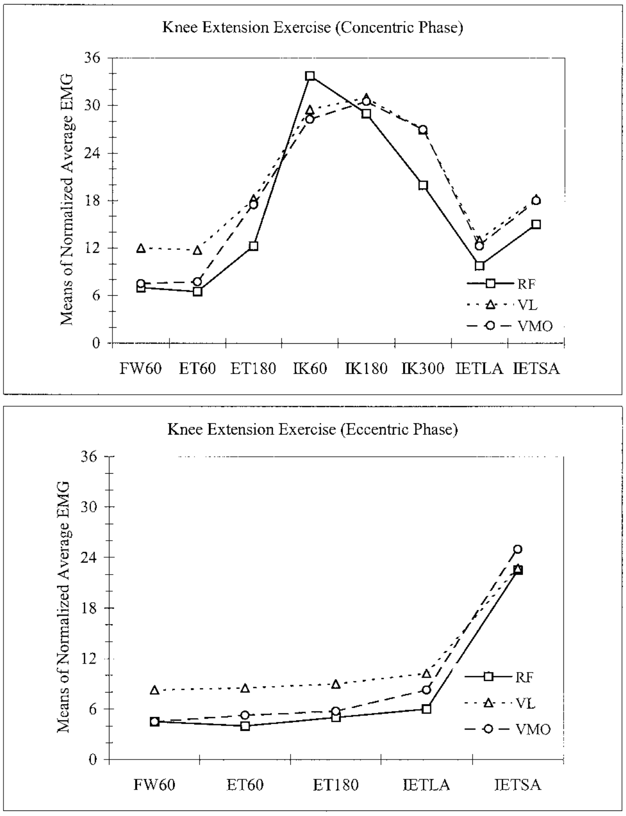


FIGURE 5—Interaction effect (muscle × exercise) across the concentric (*top*) and eccentric (*bottom*) phases of the eight seated quadriceps exercises. FW60, free-weight at 60°·s^{-1}; ET60, elastic tubing at 60°·s^{-1}; ET180, elastic tubing at 180°·s^{-1}; IK60, isokinetic at 60°·s^{-1}; IK180, isokinetic at 180°·s^{-1}; IK300, isokinetic at 300°·s^{-1}; IETLA, Inertial Exercise Trainer®, large-arc; IETSA, Inertial Exercise Trainer®, small arc.

TABLE 4. *Post hoc* testing results for the RF, VL, and VMO mean average normalized EMG amplitudes across the concentric phase of each seated quadriceps exercise with η^2 and observed power statistics displayed.

Exercise	Results of Repeated Measures ANOVA for Within-Subject Factor (Muscle) across Each Exercise				Results of Post Hoc Testing Using the Bonferroni Adjustment ($P < 0.05$)		
	F	$P < 0.05$	η^2	Power[a]	Significant Differences	η^2	Power
Free-weight ($60°·s^{-1}$)	15.7	Yes	0.48	1.0	VL > RF, VL > VMO	0.48	0.98
Elastic tubing ($60°·s^{-1}$)	14.3	Yes	0.46	1.0	VL > RF, VL > VMO	0.57	0.97
Elastic tubing ($180°·s^{-1}$)	7.4	Yes	0.30	0.91	VL > RF, VMO > RF	0.45	0.85
Isokinetic ($60°·s^{-1}$)	8.8	Yes	0.34	0.94	RF > VL, RF > VMO	0.44	0.84
Isokinetic ($180°·s^{-1}$)	0.4	No	0.02	0.10	Global test not significant, therefore *post hoc* testing not performed		
Isokinetic ($300°·s^{-1}$)	6.1	Yes	0.26	0.86	VL > RF, VMO > RF	0.52	0.96
Impulse IET (large arc)	2.9	Yes	0.16	0.52	No significant differences	0.31	0.54
Impulse IET (small arc)	1.8	No	0.10	0.35	Global test not significant, therefore *post hoc* testing not performed		

RF, rectus femoris; VL, vastus lateralis; VMO, vastus medialis oblique.
[a] Observed power calculations performed with $\alpha = 0.05$.

average EMG value ($P = 0.033$, power = 0.61). *Post hoc* tests examining which exercises generated greater overall quadriceps activity during eccentric muscle action are shown in Table 5.

The repeated measures ANOVAs examining the VMO/VL ratio of mean average EMG amplitude during both the concentric or eccentric muscle actions were significant ($P = 0.019$, power = 0.74; and $P = 0.001$, power = 0.99, respectively). The slow-tubing exercise demonstrated a significantly smaller VMO/VL ratio than five of the other exercises. Isokinetic exercise at $300°·s^{-1}$ demonstrated the largest VMO/VL ratio (1.15). However, this value was not significantly different from the other exercise ratios because of a large standard deviation (0.75). The IET small-arc exercise demonstrated a higher VMO/VL ratio (1.14 ± 0.54) than all other eccentric muscle activity ratios. The complete results of statistical testing of the VMO/VL mean average EMG ratio in both the concentric and eccentric phases are shown in Figure 6.

DISCUSSION

Quadriceps EMG Activity

Muscle activation patterns for eight seated quadriceps exercises using four different types of resistance were quantified in this study. All descriptive EMG data was expressed in terms of mean normalized average and peak EMG amplitude (Table 3). Average amplitude takes into consideration both time and magnitude. In contrast, peak amplitude represents maximal EMG activity during a single instant in time. Greater average amplitudes suggest that the exercise is effective in activating the muscle throughout the whole ROM. Large peak amplitudes may warn the researcher that this exercise is not appropriate for patients with injuries where increased muscle forces may disrupt soft tissue healing or recent surgical repairs. Therefore, the researcher and clinician should consider both peak and average muscle activity when prescribing exercise. Hintermeister et al. have remarked, "in combination average and peak amplitude can give a more complete understanding of muscle activity" (14).

TABLE 5. *Post hoc* testing results of mean average normalized EMG amplitude for the main effect of exercise across the eccentric phase of the eight seated quadriceps exercises.

Exercise	Significant Differences Found Using Bonferroni Procedure for Multiple Comparisons ($P < 0.05$, $\eta^2 = 0.87$, power = 1.0)
Free-weight ($60°·s^{-1}$)	< Elastic tubing $180°·s^{-1}$, < IET (large arc), < IET (small arc)
Elastic tubing ($60°·s^{-1}$)	< Elastic tubing $180°·s^{-1}$, < IET (large arc), < IET (small arc)
Elastic tubing ($180°·s^{-1}$)	> Free-weight $60°·s^{-1}$, > elastic tubing $60°·s^{-1}$, < IET (small arc)
Impulse IET (large arc)	> Free-weight $60°·s^{-1}$, > elastic tubing $60°·s^{-1}$, < IET (small arc)
Impulse IET (small arc)	> Free-weight $60°·s^{-1}$, > elastic tubing $60°·s^{-1}$, > elastic tubing $180°·s^{-1}$, > IET (large arc)

Five of the seated quadriceps exercises in this study had an eccentric component. In all but one of the eccentric phases of the five exercises, the mean peak and average normalized amplitudes of concentric EMG activity were larger than the corresponding eccentric EMG amplitudes (Table 3), and this is consistent with the findings of others (4,14,15). The rationale for why concentric EMG activity is greater than eccentric EMG is explained by the superior metabolic efficiency of muscle lengthening (4). The reason this did not hold true for the IET small-arc exercise in this study may be explained by the following hypothesis. The above concept only holds true when the concentric and eccentric phases of the exercise involve the same force.

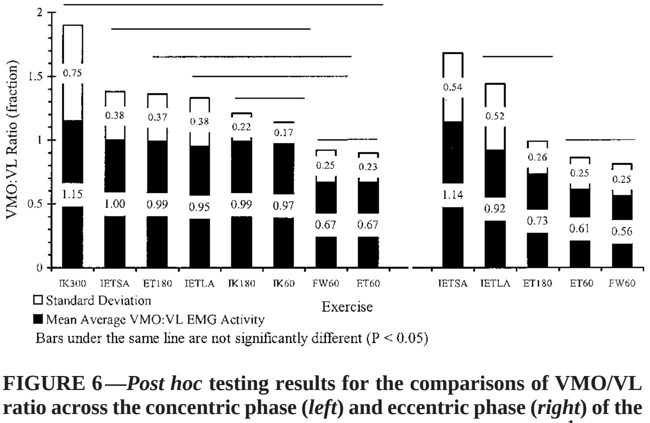


FIGURE 6—*Post hoc* testing results for the comparisons of VMO/VL ratio across the concentric phase (*left*) and eccentric phase (*right*) of the eight seated quadriceps exercises. FW60, free-weight at $60°·s^{-1}$; ET60, elastic tubing at $60°·s^{-1}$; ET180, elastic tubing at $180°·s^{-1}$; IK60, isokinetic at $60°·s^{-1}$; IK180, isokinetic at $180°·s^{-1}$; IK300, isokinetic at $300°·s^{-1}$; IETLA, Inertial Exercise Trainer®, large-arc; IETSA, Inertial Exercise Trainer®, small arc.

Although examination of Table 2 reveals that both the concentric and eccentric phase of the IET small-arc exercise reached a peak applied load of 239 N, one cannot be sure of how long this load was applied to the subject's limb. Perhaps during the IET small-arc exercise the peak load was applied for a longer period. It may also be important to note the large standard deviation in the peak load (±103 N) during the eccentric muscle phase (Table 2).

It is difficult to compare these results with other studies (6,10,12,19,23,30,35) because of the different EMG processing procedures, methodological variances in the performance of quadriceps exercises, and the amount of load used for resistance. However, similar to this study, Mirzabeigi et al. (23) found 0° to 90° isokinetic knee extension at an angular velocity of $60°\cdot s^{-1}$ to elicit the highest amount of RF, VL, and VMO muscle activity when compared with isometric knee extension and side-lying free-weight quadriceps exercises.

Selective activation of the superficial quadriceps muscles. The rectus femoris displayed the greatest variability across concentric extension exercises among the three superficial quadriceps muscles measured. Several possible explanations are presented. First, the three superficial quadriceps muscles differ substantially in size. The cross-sectional area of the RF is only about a third of the VL, so its relative contribution to the overall quadriceps force is different. Second, the RF is a two-joint muscle with its origin on the ilium. If the hip was not stabilized during seated knee extensions, potentially less concentric muscle force may have been generated. The lack of a thigh strap during isokinetic exercise may have explained the large difference in RF activity between the slow and fast isokinetic angular velocities. At $300°\cdot s^{-1}$, the thigh strap may have provided increased joint stabilization and decreased inertial forces (24). It may have accomplished this by stabilizing the proximal RF muscle, allowing greater muscle activity to occur. Further studies examining RF recruitment during isokinetic seated quadriceps exercises are necessary to confirm these findings.

A VMO/VL ratio of 1.1 ± 0.4 was reported by Cerny (6) when examining the integrated EMG activity of the quadriceps during seated quadriceps exercises using ankle weights (5% subject's body weight). This is in contrast to the VMO/VL ratio of 0.67 ± 0.23 found in this study for the free-weight seated quadriceps exercise using a 7.9-kg ankle weight. Examination of the VMO/VL ratios for the other quadriceps exercises performed in this study revealed several significant findings (Fig. 6). During both concentric and eccentric phases, the IET small-arc exercise had a significantly higher VMO/VL EMG activity ratio than either the free-weight or tubing exercises. No significant differences in VMO/VL activation between the IET and Cybex® exercises were found. The elastic tubing exercise at $180°\cdot s^{-1}$ had a significantly higher VMO/VL ratio than the elastic tubing exercise at $60°\cdot s^{-1}$ for both concentric and eccentric phases. These results demonstrate that by changing the type of resistance and/or the knee joint angular velocity, the VMO/VL ratio can be influenced. Whether this holds true for patients with VMO weakness and knee pathology is unclear and requires further investigation. When examining the VMO/VL ratio of an exercise, it is also important to consider the principle of muscle overloading. Investigators (30) have stated that even if greater VMO EMG activity could be obtained relative to the VL, the magnitude of the VMO contraction would need to be 60% of maximum or greater to stimulate hypertrophy. The only concentric seated quadriceps exercises in this study that accomplish the goal of peak activity greater than 60% of maximum were the isokinetic and IET small-arc exercises. The only eccentric exercise to reach this goal was the IET small-arc exercise (Table 3).

Resistance Devices

The blue Thera-Band® elastic tubing demonstrated similar EMG activation and peak load in comparison to the free weight exercise performed at the same angular velocity (Tables 1 and 3). On the basis of these results, it appears that elastic resistance is a viable alternative to the use of free weights of similar resistance. The linear resistance equations from this study (Fig. 1) and in the study by Hughes et al. (17) allow clinicians to provide patients with a more accurate depiction of the resistance provided by elastic tubing devices. The relatively low cost and portability of this tubing makes it an ideal tool in the rehabilitation setting.

As expected, isokinetic resistance provided the greatest total mean average quadriceps activity in this study. The knee joint angular velocity and ROM data (Table 1) reinforced the known limitations of the isokinetic dynamometer used in this study. All subjects in this study were inexperienced in performing isokinetic exercise. This may explain the large variability seen in the angular velocity data at $300°\cdot s^{-1}$. Actual measured average angular velocities of the subject's leg across the concentric contractions were 10°, 35°, and $41°\cdot s^{-1}$ less than the preset dynamometer velocities. This supports the recommendation of Chow et al. (7) that actual angular velocity data be measured with a separate measurement device when the dynamometer is used for research. A limitation of this study was that the applied forces during the isokinetic exercises were not measured. This would have required a specialized load cell to be placed between the subject's leg and the dynamometer shin pad. The absence of these data and the inability of this dynamometer to provide eccentric forces prevented the comparisons of isokinetic applied loads with the applied loads of the other seated quadriceps exercises.

The Impulse IET is a relatively new resistance device that applies inertial loading as resistance (1,2,28,33). Load cell data confirmed that the large forces (239 N) were generated in a very short time period (<231 ms). A representative trial of a single subject's load cell and electrogoniometer data is shown in Figure 7. Examination of this figure reveals the IET's ability to generate large forces over a short time period. This also shows that limiting ROM can increase eccentric loading during tonic exercise. It is interesting to note that the inertial load figure for the small-arc exercise

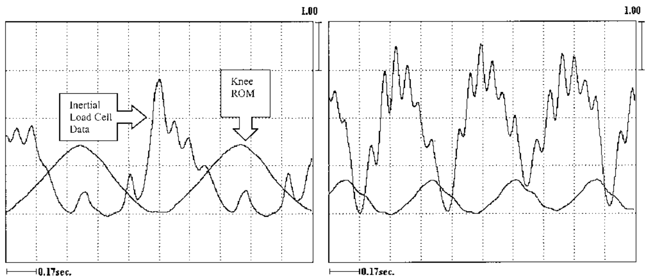


FIGURE 7—Right knee ROM and load cell data for the IET large-arc exercise (*left*) and the IET small-arc seated quadriceps exercise (*right*).

slightly resembles an isokinetic torque curve. The relationship between isokinetic exercise and part of the inertial exercise cycle has been previously recognized by Albert (2). The IET exercises required the greatest amount of skill from the subjects. None of the subjects had prior experience or exposure to lower extremity inertial exercise before the orientation session. Lack of experience likely prevented subjects from generating even higher knee joint angular velocities. This inexperience was not considered a limitation, as most first-time users in a clinical setting would be inexperienced with this device as well. A possible limitation of this study was the absence of an inertial seated quadriceps exercise using the phasic exercise method. A recent study by Phillips et al. (28) showed that the phasic IET exercise generated a 50-N greater load than tonic IET exercise in two subjects performing shoulder external rotation/internal rotation. It is unknown if similar differences in generated loads between the phasic and tonic exercise protocols would exist in the lower extremity. The results of this study showed that the Impulse IET can isolate quadriceps muscle activity and is a resistance device that warrants further investigation for lower extremity rehabilitation in both athletic and nonathletic populations.

Use of Seated Quadriceps Exercises in Quadriceps Strengthening

Several studies (6,10,23,35) have compared the EMG activity of seated quadriceps exercises with exercises such as the squat and horizontal leg press. Escamilla et al. (10) compared the EMG activity of the RF, VL, and VM during the squat, leg press, and seated quadriceps exercises. These investigators found that the seated quadriceps exercise generated approximately 45% more RF activity than the leg press and squat, whereas the squat and leg press generated 20% more VM and 5% more VL activity than the seated quadriceps exercises. However, it was also found that this might only be true at certain arcs in the exercise ROM (10). Quadriceps activity was significantly greater in the seated knee extension exercise from 15° to 65°, whereas quadriceps activity was significantly greater in the leg press and squat at knee angles greater than 83°. These results are similar to the findings of Wilk et al. (35). These investigators found maximal quadriceps EMG activity during the squat at 88° to 102° of knee extension and maximal quadriceps EMG activity from 35° to 11° of knee extension during the seated knee extension exercises. These studies demonstrate the importance of considering different ROM and exercise selection depending on therapeutic intention. Unfortunately, some clinicians fail to fully integrate both types of exercise into their rehabilitation programs. In an exercise, such as the squat, multiple joints and multiple muscle groups are involved. These exercises are advocated in knee rehabilitation because they minimize shear forces and provide muscular cocontraction during terminal knee extension (10,35). This becomes very important in certain instances, such as after an anterior cruciate ligament (ACL) repair (27). Therefore, seated quadriceps exercises from 0° to 40° are often avoided by clinicians during ACL rehabilitation because they produce high levels of anterior shear (10,35). However, successful overloading and isolated strengthening of the quadriceps femoris muscle without seated, single-joint, isolated knee extension exercises is difficult. This is because the proximal and distal muscles used during the multijoint exercises, such as the leg press and squat, may mask isolated quadriceps weakness. Therefore, seated quadriceps exercises may be integrated into the program as soon as appropriate. Using an anterior tibial shear pad during isokinetic exercise (8), using elastic tubing, and/or the IET in greater than 45° flexion are possible alternative forms of seated quadriceps exercises that may protect the ACL graft and isolate the superficial quadriceps muscles.

This research has defined an exercise continuum for seated quadriceps exercises in the clinical setting. On the basis of the study results, seated quadriceps exercises could be incorporated into a quadriceps strengthening program in the following order of increasing quadriceps activity: free-weight or elastic tubing exercises at a slow speed ($60°\cdot s^{-1}$), IET large-arc (60°) exercises, elastic tubing exercises at a fast speed ($180°\cdot s^{-1}$), IET small-arc (30°) exercises, and isokinetic exercise ($300°\cdot s^{-1}$, $180°\cdot s^{-1}$, and $60°\cdot s^{-1}$). It is important that this exercise progression is not examined in isolation. These results were generated from a young population without current knee pathology. Clinicians should make their exercise decisions on the basis of patient diagnosis, consideration of internal joint forces, soft tissue healing, muscle activation goals, and the physical properties (rate of loading, applied load, variability of resistance) of the resistance device. The findings of this study suggest clinicians should consider biomechanical and resistance data when developing a quadriceps strengthening program. Some seated quadriceps exercises may be more appropriate for reaching certain rehabilitation goals than others.

CONCLUSION

In summary, the results of this study provide significant evidence to partially reject the first research hypothesis and fully reject the second hypothesis. A significant interaction between RF, VL, and VMO muscle activity and the type of exercise performed was found. However, this only occurred during concentric muscle activity. No interaction effect was found during eccentric muscle activity. Certain exercises did produce higher eccentric quadriceps muscle activity. No portion of any seated quadriceps exercise selectively isolated the VMO. Investigations of the VMO/VL ratio revealed different mean average EMG muscle activity levels among exercises.

This study also demonstrated that not all seated quadriceps exercises produce the same mean average quadriceps EMG activities. Furthermore, knee joint angular velocity and the type of resistance chosen affected muscle activity. This study was the first to examine and quantify inertial loading of the lower extremity as well as compare it with other types of resistance devices.

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REFERENCES

1. Albert, M. S., E. Hillegass, and P. Spiegel. Muscle torque changes caused by inertial exercise training. *J. Orthop. Sports Phys. Ther.* 20:254–261, 1994.
2. Albert, M. S. *Eccentric Muscle Training in Sports and Orthopedics.* New York: Churchill Livingstone, 1991, pp. 75–97.
3. Bandy, W. D., and S. McLaughlin. Intramachine and intermachine reliability for selected dynamic muscle performance tests. *J. Orthop. Sports Phys. Ther.* 18:609–613, 1993.
4. Basmaijan, J. V., and C. De Luca. *Muscles Alive: Their Functions Revealed by Electromyography.* Baltimore: Williams & Wilkins, 1985, pp. 187–200.
5. Campnella, B., C. G. Mattacola, and I. F. Kimura. Effect of visual feedback and verbal encouragement on concentric quadriceps and hamstring peak torque of males and females. *Isokin. Exerc. Sci.* 8:1–6, 2000.
6. Cerny, K. Vastus medialis oblique/vastus lateralis muscle activity ratios for selected exercises in persons with and without patellofemoral pain syndrome. *Phys. Ther.* 75:672–683, 1995.
7. Chow, J. W., W. G. Darling, and J. G. Hay. Mechanical characteristics of knee extension exercises performed on an isokinetic dynamometer. *Med. Sci. Sports Exerc.* 29:794–803, 1997.
8. Davies, G. J. *A Compendium of Isokinetics in Clinical Usage.* Onalaska, WI: S&S Publishers, 1992, pp. 33–50 and 283–374.
9. Delagi, E. F., and A. O. Perotto. *Anatomic Guide for the Electromyographer*. Springfield, IL: Charles C Thomas, 1981, pp. 180–200.
10. Escamilla, R. F., G. S. Fleisig, N. Zheng, S. W. Barrentine, K. E. Wilk, and J. R. Andrews. Biomechanics of the knee during closed kinetic chain and open kinetic chain exercises. *Med. Sci. Sports Exerc.* 30:556–569, 1998.
11. Fullkerson, J., and D. Hungerford. *Disorders of the Patellofemoral Joint*, 3rd Ed. Baltimore: Williams & Wilkins, 1997, pp. 1–365.
12. Grabiner, M. D., T. J. Koh, and L. von Haefen. Effect of concomitant hip joint adduction and knee extension forces on quadriceps activation. *Eur. J. Exp. Musculoskel. Res.* 1:121–124, 1993.
13. Harrelson, G. L., and D. Leaver-Dunn. Introduction to rehabilitation. In: *Physical Rehabilitation of the Injured Athlete*, J. R. Andrews, G. L. Harrelson, and K. E. Wilk (Eds.). Philadelphia: W. B. Saunders Company, 1998, pp. 175–218.
14. Hintermeister, R. A., G. W. Lange, J. M. Schulthies, M. J. Bey, and R. J. Hawkins. Electromyographic activity and applied load during shoulder rehabilitation exercises using elastic resistance. *Am. J. Sports Med.* 26:210–220, 1998.
15. Hintermeister, R. A., M. J. Bey, G. W. Lange, J. R. Steadman, and C. J. Dillman. Quantification of elastic resistance knee rehabilitation exercises. *J. Orthop. Sports Phys. Ther.* 28:40–50, 1998.
16. Huck, S. W. *Reading Statistics and Research.* New York: Addison Wesley Longman, Inc., 2000, pp. 467–499.
17. Hughes, C. J., K. Hurd, A. Jones, and S. Sprigle. Resistance properties of Thera-Band tubing during shoulder abduction exercise. *J. Orthop. Sports Phys. Ther.* 29:413–420, 1999.
18. Johnson, J., and D. Siegel. Reliability of an isokinetic movement of the knee extensors. *Res. Q.* 3:88–90, 1979.
19. Karst, G. M., and P. D. Jewett. Electromyographic analysis of exercises proposed for differential activation of the medial and lateral quadriceps femoris muscle components. *Phys. Ther.* 73: 286–299, 1993.
20. Kovaleski, J. E., and R. J. Heitman, Testing and training the lower extremity. In: *Isokinetics in Human Performance*, L. E. Brown (Ed.). Champaign, IL: Human Kinetics, 2000, pp. 171–196.
21. Lieb, F., and J. Perry. Quadriceps function: an anatomical and mechanical study using amputated limbs. *J. Bone Joint Surg. Am.* 53:1535–1548, 1971.
22. Mikesky, A. E., R. Topp, J. K. Wigglesworth, D. M. Harsha, and J. E. Edwards. Efficacy of a home-based training program for older adults using elastic tubing. *Eur. J. Appl. Physiol.* 69:316–320, 1994.
23. Mirzabeigi, E., C. Jordan, J. K. Gronley, N. L. Rockowitz, and J. Perry. Isolation of the vastus medialis oblique muscle during exercise. *Am. J. Sports Med.* 27:50–53, 1999.
24. Osternig, L. R. Assessing human performance. In: *Isokinetics in Human Performance*, L. E. Brown (Ed.). Champaign, IL: Human Kinetics, 2000, pp. 77–91.
25. Page, P. A., A. Labbe, and R. V. Topp. Clinical force production of Thera-Band® elastic bands (Abstract PO35). *J. Orthop. Sports Phys. Ther.* 30:A47, 2000.
26. Page, P. A., J. Lamberth, B. Abadie, R. Boling, R. Collins, and R. Linton. Posterior rotator cuff strengthening using Thera-Band® in a functional diagonal pattern in collegiate baseball pitchers. *J. Athletic Training* 28:346–354, 1993.
27. Paulos, L., F. R. Noyes, and E. Grood. Knee rehabilitation after anterior cruciate ligament reconstruction and repair. *Am. J. Sports Med.* 9:140–149, 1983.
28. Phillips, T. C., S. S. Kohles, J. F. Orwin, L. T. Brody, R. P. McCabe, and R. Vanderby, Jr. Instrumentation to quantify exercise using an impulse inertial system. *J. Appl. Biomech.* 16:60–67, 2000.
29. Pincivero, D. M., W. S. Gear, N. M. Moyna, and R. J. Robertson. The effects of rest interval on quadriceps torque and perceived exertion in healthy males. *J. Sports Med. Phys. Fitness* 39:294–249, 1999.
30. Powers, C. M. Rehabilitation of the patellofemoral joint disorders: a critical review. *J. Orthop. Sports Phys. Ther.* 28:345–354, 1998.
31. Soderberg, G. L., and L. M. Knutson. A guide for use and interpretation of kinesiologic electromyographic data. *Phys. Ther.* 80:485–498, 2000.
32. Souza, D. R., and M. T. Gross. Comparison of vastus medialis oblique:vastus lateralis muscle integrated electromyographic ratios between healthy subjects and patients with patellofemoral pain. *Phys. Ther.* 71:310–316, 1991.
33. Tracy, J. E., S. Obuchi, and B. Johnson. Kinematic and electromyographic analysis of elbow flexion during inertial exercise. *J. Athletic Training* 30:254–258, 1995.
34. Türker, K. S. Electromyography: some methodological problems and issues. *Phys. Ther.* 73:698–710, 1993.
35. Wilk, K. E., R. F. Escamilla, G. S. Fleisig, S. W. Barrentine, J. R. Andrews, and M. L. Boyd. A comparison of tibiofemoral joint forces and electromyographic activity during open and closed kinetic chain exercises. *Am. J. Sports Med.* 24:518–537, 1996.