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ORIGINAL ARTICLE

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Effects of unilateral isometric strength training on joint angle specificity and cross-training

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Abstract The purpose of this study was to examine the effects of unilateral isometric leg extension strength training on the strength and integrated electromyogram (IEMG) of both the trained and untrained limbs at multiple joint angles. A training (TRN) group [nine women; mean (SD) age, 20(1) years] exercised for 6 weeks with isometric leg extensions at 80% of maximal isometric torque. A control (CTL) group [eight women; 21(1) years] did not exercise. The training was performed three times per week on a Cybex II isokinetic dynamometer at a joint angle where the lever arm was 0.79 rad below the horizontal plane. The subjects were tested pre- and posttraining for maximal unilateral isometric torque in both limbs at joint angles of zero, 0.26, 0.79, 1.31, and 1.57 rad below the horizontal plane. Bipolar surface electrodes were used to record the IEMG of the vastus lateralis (VL) and vastus medialis (VM) during the isometric tests. Three univariate (torque, IEMG-VL, and IEMG-VM) four-way (group × time × limb × angle) mixed factorial ANOVAs were used to analyze the data. The results indicated joint angle specificity for isometric torque in the TRN group only, with significant increases in torque at 0.79 ($P = 0.0004$) and 1.31 ($P = 0.0039$) rad. No significant increases in torque were found in the untrained limb of the TRN group or in either limb of the CTL group. Similarly, there were no significant changes in IEMG as a result of the training for the VL or VM. The joint-angle-specific strength increases without concomitant increases in IEMG were hypothesized to result from joint-angle-specific decreases in antagonistic co-contraction and/or preferential hypertropy of the quadriceps femoris at specific levels of the muscle group.

Key words Electromyography · Resistance training

Introduction

The adaptations following isometric strength training have been shown to be highly specific. Typically, increases in strength have been shown to occur at limited points in the range of joint motion for the trained muscles (Lindh 1979; Thepaut–Mathieu et al. 1988; Kitai and Sale 1989). The extent of joint angle specificity, however, is still unclear. Investigations reporting joint angle specificity have indicated different responses depending on the joint angle at which training occurred and the muscle group involved (Lindh 1979; Knapik et al. 1983; Thepaut–Mathieu et al. 1988; Kitai and Sale 1989; Weir et al. 1994).

Joint angle specificity has been suggested to result from neurological adaptations (Thepaut–Mathieu et al. 1988; Kitai and Sale 1989). Thepaut–Mathieu et al. (1988) found increases in the ratio of trained joint angle maximal electromyographic (EMG) activity versus untrained joint angle maximal EMG, indicating an increase in maximal neural drive at the trained joint angle following training. In addition, Kitai and Sale (1989) did not find increases in maximal evoked plantarflexion torque at joint angles exhibiting increases in voluntary strength, further indicating a possible "neural adaptation" associated with joint angle specificity.

Strength training has also been shown to result in cross-training, in which training one limb results in strength increases in the untrained contralateral limb (Enoka 1988). While not always exhibited (Jones and

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Rutherford 1987; Garfinkel and Cafarelli 1992), cross-training has been shown to occur following isotonic (Shaver 1975; Moritani and deVries 1979; Houston et al. 1983; Brown et al. 1990), isokinetic (Krotkiewski et al. 1979; Housh et al. 1992), and isometric (Ikai and Fukunaga 1970; Cannon and Cafarelli 1987) strength training, as well as following electrical muscle stimulation training (Laughman et al. 1983; Carbic and Appell 1987). These results have also been suggested to be a function of neurological adaptations (Ikai and Fukunaga 1970; Komi et al. 1978; Moritani and de-Vries 1979), in which the training results in an increase in neural drive to the untrained muscles. The question of whether joint angle specificity is evident in the untrained limb following isometric training, and what role changes in neural drive have in these phenomena, has yet to be fully examined. A previous investigation has shown cross-training following isometric strength training to be joint-angle-specific for leg extension (Weir et al. 1994). However, EMG measures from the vastus lateralis (VL) did not show increases in amplitude specifically at the joint angles where increases in strength were found. It was hypothesized that the dissociation between strength increases and increases in EMG amplitude of the VL may have been due to increased EMG activity of other muscles in the quadriceps femoris group, such as the vastus medialis (VM). Therefore, the purpose of this investigation was to examine this hypothesis by isometrically strength training the quadriceps femoris group of the right limb and testing both limbs for increases in joint-angle-specific strength and IEMG of the VM and VL.

Methods

Subjects

Seventeen female college students volunteered for this investigation and were divided into a control (CTL) group ($n = 7$) and a training (TRN) group ($n = 9$). The descriptive characteristics of the subjects are presented in Table 1. The subjects had not been involved in a strength training program for the previous 6 months and were instructed not to alter their activity patterns during the study. Informed consent was received from each subject prior to inclusion in the study and all procedures were approved by the Institutional Review Board.

Table 1 Descriptive characteristics of the subjects [mean (SD); *TRN* training, *CTL* control]

	TRN group Pretest	Posttest	CTL group Pretest	Posttest
Age (years)	20(1)		21(1)	
Height (cm)	168(7)		169(6)	
Mass (kg)	59(8)	60(8)	62(7)	61(6)

Training protocol

The subjects in the TRN group performed 6 weeks of isometric strength training of the right quadriceps femoris muscle group on a calibrated Cybex II isokinetic dynamometer (Lumex, Ronkonkoma, N.Y., USA). The training was conducted three times per week with 1 day of rest between training sessions in the same week and 2 days of rest over the weekend. Each training session consisted of two sets of isometric leg extensions at a torque equal to 80% of each subject's maximal voluntary contraction (MVC). Preliminary MVC values were determined from the pretraining test session. At the end of the 2nd and 4th weeks of training, MVC values were reassessed and the training torque values were increased accordingly. Each set consisted of ten repetitions with 30 s of rest between repetitions and 2 min of rest between sets. Each repetition lasted 6 s and was performed at a joint angle in which the dynamometer lever arm was 0.79 rad below the horizontal plane. The CTL group did not train and maintained their normal daily activities.

MVC measurements

Following a warm-up consisting of 5 min of unloaded cycling and static stretching of the quadriceps, the subjects performed a total of 20 (ten repetitions per limb) maximal isometric leg extensions on the dynamometer. The subjects were positioned on the dynamometer such that the axis of rotation of the lever arm was aligned as closely as possible to the axis of rotation of the knee. The length of the lever was adjusted so that the shin pad was placed just proximal to the malleoli. To allow consistent positioning for all testing and training sessions, recordings were made of the dynamometer height, length of the lever arm, and position of the dynamometer relative to the dynamometer chair.

The subjects were tested at joint angles where the dynamometer lever arm was zero, 0.26, 0.79, 1.31, and 1.57 rad below the horizontal plane. Each subject performed two maximal isometric contractions at each joint angle in which the subjects were verbally encouraged to produce as much force as possible. A minimum of 2 min of rest was allowed between each contraction. The order of testing of the joint angles and the order of testing of the limbs was randomized during the pretraining test session. The pretraining order of testing was followed during the posttraining test session.

EMG measurements

During all isometric strength tests, measures of the surface integrated EMG of the VL (IEMG-VL) and VM (IEMG-VM) were recorded. A bipolar lead system using silver–silver chloride electrodes was employed with the head of the fibula serving as the anatomical landmark for the reference electrode. The pick-up electrodes were located over the VM as recommended by Zipp (1982). Briefly, the pick-up electrodes were located over the VM at a level approximately 20% of the distance along a line connecting the medial gap of the knee to the anterior superior iliac spine. For the VL, the pick-up electrodes were located between the base of the patella and the inguinal ligament (Weir et al. 1994). The interelectrode spacing (center to center) was 2.5 cm for all subjects. To ensure consistent electrode placement for the posttraining test sessions, marks were applied to the subjects' skin around the circumference of the electrodes with silver nitrate applicators. For all tests, the skin was abraded until the interelectrode impedance was below 2000 Ω.

The EMG activity was measured using two digital multimeters (EMG 1000, National Medical Sales, Laguna Niguel, Calif.) set for a 1-s integration period. The characteristics of this device have been previously described in detail (deVries et al. 1990). Briefly, this device provides a digital readout of the mean rectified IEMG value with a bandwidth of 10–300 Hz at the 3-dB level and a 60-Hz common mode rejection ratio of 100 dB.

Statistical analyses

From the pretraining and posttraining test sessions, the maximal torque and corresponding IEMG values for each joint angle were used in the statistical analyses. The data were analyzed with three (dependent variables were isometric torque, IEMG-VL, and IEMG-VM) four-factor mixed factorial analyses of variance (ANOVA) with the Huynh–Feldt adjustment (Keppel 1982). The between factor was group (TRN vs CTL). The three within-subjects factors were time (pre-vs posttraining), limb (right vs left), and joint angle. An alpha of 0.05 was considered significant for all analyses.

Results

For the torque analysis, there was a significant [$F(4, 60) = 3.93$; $P = 0.0067$] four-way (time × angle × limb × group) interaction. The four-way model was subsequently decomposed into two separate three-way repeated measures ANOVAs (time × angle × limb) for the TRN and CTL groups. For the TRN analysis, there was a significant time × limb × angle interaction [$F(4, 32) = 10.89$; $P < 0.0001$]. This was further analyzed with two (right and left limb) two-way ANOVAs (time × angle). For the left (untrained) limb, there was no interaction or main effect for time (Fig. 1). However, for the right (trained) limb, there was a significant [$F(3.9, 31.1) = 14.9$; $P < 0.0001$) time × angle interaction (Fig. 2). Subsequent pairwise comparisons (pre- to posttraining at each joint angle) with paired t-tests revealed significant increases in torque at 0.79 ($t = 5.71$; $P = 0.0004$) and 1.31 ($t = 4.0$; $P = 0.0039$) rad, representing increases of 27.4 and 7.3%, respectively. For the CTL analysis, there were no significant interactions but there was a slightly significant ($P = 0.0499$) main effect for time, such that the posttraining CTL torque values (collapsed across limb and angle) decreased from 121.2 to 116.9 Nm (3.54%; Fig. 3).

For the IEMG-VM data, there were no significant four- or three-way interactions. There was however, a significant time × limb interaction which was a function of a 7.0% increase in IEMG in the right limb and a 6.4% decrease in IEMG in the left limb from pre- to posttraining. These effects were collapsed across group and angle and were thus not central to the research questions of interest. Figure 4 shows the IEMG values for the VM across time at each joint angle.

For the IEMG-VL data, there were no significant interactions or meaningful main effects. Figure 5 shows the IEMG values for the VL across time at each joint angle.

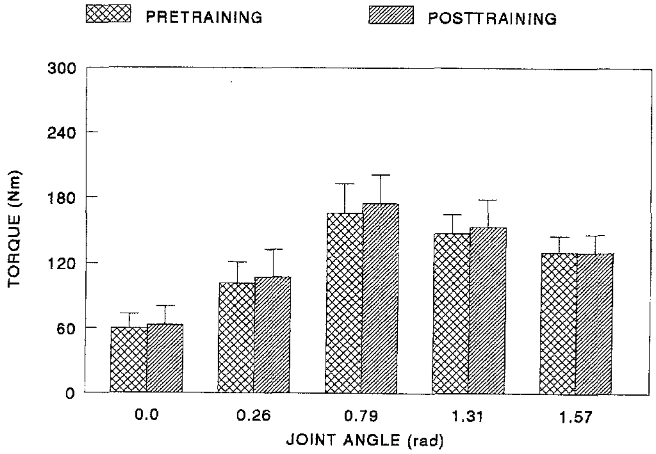

Fig. 1 Torque changes [mean (SD)] for the training (TRN) group (left limb)

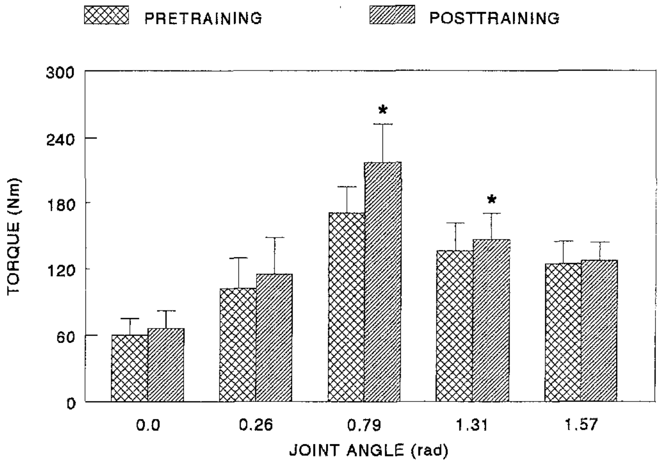

Fig. 2 Torque changes [mean (SD)] for the TRN group (right limb). $*P = 0.0004$, $**P = 0.0039$

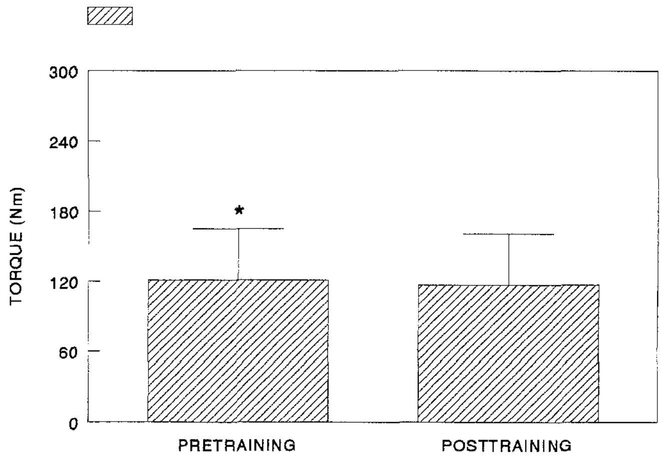

Fig. 3 Torque changes [mean (SD)] for the control (CTL) group (collapsed across limb and angle). $*P = 0.0449$

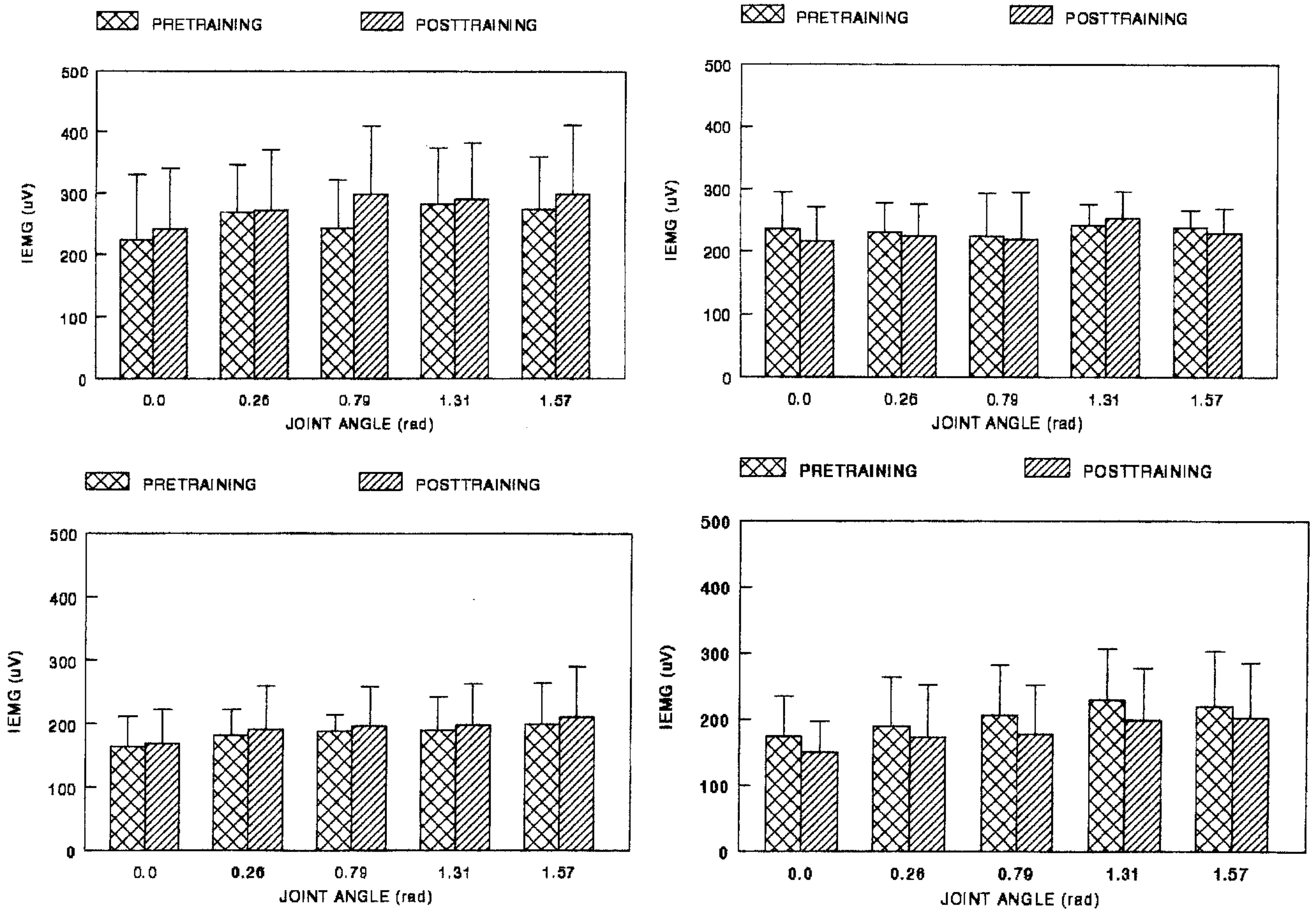

Fig. 4 Maximal integrated electromyogram (IEMG) values [mean (SD)] for the vastus medialis of the TRN and CTL groups. *Upper left* TRN group, trained limb; *upper right* TRN group, untrained limb; *lower left* CTL group, right limb; *lower right* CTL group, left limb

Discussion

The results of this investigation demonstrated joint angle specificity in which isometric strength training at a joint angle 0.79 rad below the horizontal plane resulted in significant increases in torque output at 0.79 and 1.31 rad. These results are similar to previous investigations showing joint angle specificity (Lindh 1979; Thepaut–Mathieu et al. 1988; Kitai and Sale 1989; Weir et al. 1994).

However, unlike some previous investigations (Ikai and Fukunaga 1970; Cannon and Cafarelli 1987), the present study did not result in significant strength increases in the untrained limb at any joint angle following isometric strength training. The reasons for the contradictory findings with regard to cross-training are unclear, especially considering that the training protocol of this investigation and one previous investigation reporting cross-training were identical (Weir et al. 1994). However, other previous investigations have not found cross-training (Tesch and Karlsson 1984; Garfinkel and Cafarelli 1992) or EMG evidence of increased neural drive in the contralateral limb (Cannon and Cafarelli 1987; Garfinkel and Cafarelli 1992) following isometric resistance training.

With respect to the joint angle specificity found in this investigation, there were no concomitant statistically significant increases in maximal IEMG in either the VL or the VM. The lack of evidence for a direct link between increases in neural drive as assessed by changes in IEMG and changes in muscle strength are consistent with the data of Weir et al. (1994) but contradict those of Thepaut–Mathieu et al. (1988) who reported an improvement in maximal activation at the trained joint angles following isometric training of the forearm flexors. It is interesting to note that Weir et al. (1994) as well as the present investigation examined the angle specific strength changes in the leg extensors, white Thepaut–Mathieu et al. (1988) examined the forearm flexors. A lack of association between strength and EMG changes was also found by Garfinkel and Cafarelli (1992) and Thorstensson et al. (1976) for the leg extensors.

Weir et al. (1994) have suggested that the joint angle specificity, which occurred without specific increases in IEMG of the VL, may have been a function of increases

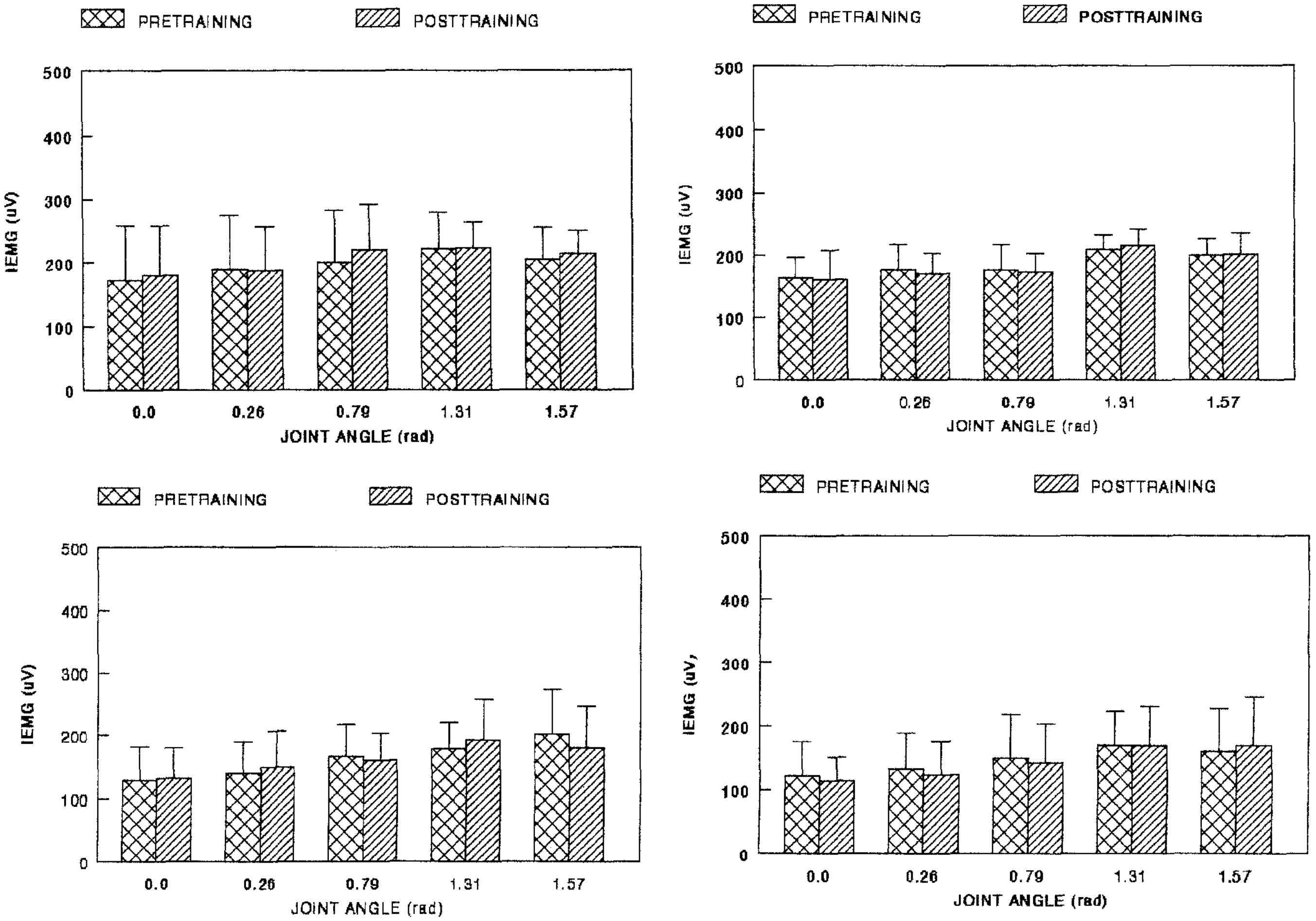

Fig. 5 Maximal IEMG values [mean (SD)] for the vastus lateralis of the TRN and CTL groups. *Upper left* TRN group, trained limb; *upper right* TRN group, untrained limb; *lower left* CTL group, right limb; *lower right* CTL group, left limb

in neural drive to other muscles of the quadriceps femoris group such as the VM. The results of the present investigation do not support this hypothesis as there were no statistically significant increases in maximal IEMG in either the VL or VM following the training period. However, since EMG recordings from the vastus intermedius (VI) and rectus femoris (RF) were not made, increases in neural drive to these muscles cannot be ruled out based on the data presented here. In addition, it should be pointed out that while changes in IEMG for the VM were not statistically significant across training, there was a 22.9% increase in IEMG at 0.79 rad.

It has been suggested that increases in muscle strength result from an interaction of increases in neural drive and muscle hypertrophy (Moritani and deVries 1979, Moritani 1992). Muscle hypertrophy, and the accompanying increase in contractile protein, results in an increase in the force production capability of individual muscle cells. Changes in neural drive may be due to increases in motor unit recruitment, increases in motor unit firing rate, and/or decreases in neuromuscular inhibition (Moritani 1992; Sale 1992). The data reported in this investigation do not provide support for changes in neural drive to either the VL or VM mediating joint-angle-specific strength increases. Garfinkel and Cafarelli (1992) have suggested that if no changes in neural drive occur, then muscular hypertrophy must be responsible for increases in muscle torque production. However, if muscle hypertrophy were the sole factor, it would seem likely that uniform increases in muscle torque production would be evident throughout the entire range of motion. The joint angle specificity reported here and elsewhere (Lindh 1979; Thepaut-Mathieu et al. 1988; Kitai and Sale 1989) does not support this contention. However, at least two possible explanations exist for these contradictory findings. First, recent evidence indicates that the levels of antagonistic co-contraction are modifiable with training (Carolan and Cafarelli 1992). A training-induced decrease in antagonistic co-contraction would result in increases in measured external torque production of the agonist(s) which would be independent of muscular hypertrophy. Consequently, as part of the "learning" (Rutherford and Jones 1986) associated with isometric strength training at a particular joint angle, the subjects may have learned to decrease co-contraction at the trained and adjacent joint angles with no learning effect at the other joint angles in the range of motion. Indeed, skill and strength levels have been reported to be inversely related to the level of co-contraction (Patton and Mortensen 1971). However, a decrease in co-contraction would also be expected to result in a decrease in reciprocal inhibition (Tyler and Hutton 1986), resulting in an increase in agonist EMG amplitude. Such was not the case for either these data or for those of Carolan and Cafarelli (1992).

Secondly, Housh et al. (1992) and Narici et al. (1989) have found that muscular hypertrophy in the quadriceps following isokinetic training is not uniform between muscles or across muscle levels. Narici et al. (1989), using magnetic resonance imaging to assess muscle cross-sectional area, have found preferential hypertrophy of the VM and VI with lesser effects in the RF and VL following isokinetic strength training. Housh et al. (1992) found significant ($P < 0.0008$) increases in cross-sectional area of the VL and VI at the middle level and in the RF at the proximal, middle, and distal level, following unilateral isokinetic strength training. Specific changes in the distribution of contractile proteins at different muscle levels and in different muscles of the quadriceps femoris may serve to alter force production (and torque production) capabilities at specific points in the range of motion. Furthermore, van Zuylen et al. (1988) have shown that motor unit subpopulations in the arm muscles exist within each muscle, that these subpopulations have their own unique activation, and that the thresholds for activation of motor units vary depending on joint angle. In addition, the muscles of a complex group like the quadriceps may have a greater mechanical advantage at certain points in the range of motion. Muscles with a greater mechanical advantage at specific joint angles may be recruited to a greater degree at those angles (van Zylen et al. 1988). If specific subpopulations of motor units within discrete areas of the muscles of the quadriceps femoris are preferentially activated during training at a specific joint angle and specific muscles are activated preferentially at specific joint angles, the training used in this investigation (80% of MVC at 0.79 rad below the horizontal plane) may have induced hypertrophic adaptations in motor unit subpopulations that contributed to increased torque production within a narrow range of motion from the training angle. Thus, hypertrophy at specific levels of the quadriceps may lead to joint angle specificity without an increase in neural drive to the VM or VL.

In summary, the results of this investigation showed joint angle specificity in the trained limb following unilateral isometric strength training of the quadriceps. No increases in strength were found in the untrained limb. In addition, no increases in IEMG of the VM or VL were associated with the joint-angle-specific strength increases. It was hypothesized that the joint angle specificity was due to a decrease in antagonistic co-contraction and/or hypertrophy of the quadriceps at specific levels.

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