Neural adaptations with sport-specific resistance training in highly skilled athletes

LARRY W. JUDGE, CHAD MOREAU‡ and JEANMARIE R. BURKE*

Department of Athletics, University of Florida, Gainesville, FL 32611, USA

The aim of this study was to assess the effects of variations in the volume and intensity of resistance training in highly skilled athletes on neural adaptive mechanisms: the maximality and pattern of neural drive. The maximality of muscle activation was measured using a high-resolution sample and hold amplifier to record interpolated twitches. The pattern of neural drive was measured by analysing isometric torque–time curves and electromyographic (EMG) characteristics during the performance of rapid isometric contractions at maximal effort. The volume and intensity of training were varied at 4-weekly intervals to systematically emphasize the development of strength, power and motor performance in 14 highly skilled track and field athletes (e.g. discus, hammer, javelin, shot put and weight). Knee extension strength increased significantly by 15% during steady maximal isometric contractions and by 24% during rapid isometric contractions at maximal effort after the 16-week training programme ($P < 0.05$). Increases in EMG amplitude and rate of EMG activation indicated that improvements to the pattern of neural drive occurred with sport-specific resistance training ($P < 0.05$). The maximality and pattern of neural drive did not change in the control group.

Keywords: human neuromuscular system, isometric strength gains, neural drive.

Introduction

Neural adaptations after resistance training among initially untrained individuals include earlier activation, extra doublets and increases in maximal discharge rates of single motor units (Kamen *et al.*, 1998; Van Cutsem *et al.*, 1998). In individuals with a prolonged background in strength training, the profile of neuromuscular adaptations to systematic variations in training load and intensity consist of concomitant changes to muscle strength and maximal levels of electromyographic (EMG) activity with only minor changes to muscle size (Hakkinen *et al.*, 1987, 1988, 1991). These data tend to support the hypothesis that contributions of neural adaptations to periodic strength gains may be greater than hypertrophic adaptations in highly trained athletes (Hakkinen *et al.*, 1985a, 1987, 1988; Hakkinen, 1989; Hakkinen and Pakarinen, 1991; Hakkinen and Kallinen, 1994). It has also been hypothesized that neural adaptations induced by periodization of training

may be essential for improving the technical aspects of athletic skill performance (Sale, 1988; Hakkinen, 1989; Moritani, 1993; Kramer *et al.*, 1998). Scientific evidence for this hypothesis is lacking, because systematic evaluations of sport-specific resistance training programmes in highly skilled athletes are limited.

The aim of this study was to assess the effects of variations in the volume and intensity of resistance training in highly skilled athletes on neural adaptive mechanisms: the maximality and pattern of neural drive (Enoka, 1997). The maximality of muscle activation was measured using a high-resolution sample and hold amplifier to record interpolated twitches (Hales and Gandevia, 1988; Allen *et al.*, 1995). The pattern of neural drive was measured by analysing isometric torque–time curves and EMG characteristics during the performance of rapid isometric maximal voluntary contractions (MVCs) (Hakkinen *et al.*, 1985a,b).

Methods

Participants and experimental design

During a 16-week sport-specific resistance training programme, neuromuscular adaptations in the right quadriceps muscle of 14 collegiate field event athletes

---

* Address all correspondence to Jeanmarie R. Burke, New York Chiropractic College, Research Department, 2360 State Route 89, Seneca Falls, NY 13148, USA. e-mail: jburke@nycc.edu
‡ *Present address:* Horrigan Sports Chiropractic Soft Tissue and Athletic Injuries, 2080 Century Park East, Ste 605, Los Angeles, CA 90067, USA.

(8 males, 6 females; height 1.82 ± 0.09 m; mean $\pm s$) were assessed monthly between September (pre-training) and December. The events participated in included the discuss, hammer, javelin, shot put and weight. All procedures were approved by the local ethics committee. Eight college-aged individuals (5 males, 3 females; height 1.72 ± 0.07 m) served as the control group. For the duration of the study, the control group was not allowed to participate in resistance training, but they were instructed to maintain their normal pattern of physical activity. The control group was tested in September and November. The physical characteristics of the participants are summarized in Table 1.

Training

The athletes followed individual training schedules designed by their Olympic level coaching staff. The coaching staff supervised all training sessions to substantiate strict adherence to the training schedules. All training schedules were divided into four phases: (1) strength conditioning phase, weeks 1–4; (2) strength development phase, weeks 5–8; (3) strength–power phase, weeks 9–12; and (4) peaking and maintenance phase, weeks 13–16. Laboratory assessments of neuromuscular performance were performed at the end of each training phase. The data collected after the strength conditioning phase served as the pre-training baseline values in an attempt to control for variations in the athletes' adherence to their off-season conditioning programmes.

The goals of the sport-specific resistance training programme were to develop maximal strength and power of the major muscle groups of the upper and lower extremities and the trunk as well as to improve strength, power and techniques that are specific to throwing field implements (Judge, 1992). Exercises included the following: warm-up and flexibility drills, a general strength circuit consisting of many body weight exercises, medicine ball and plyometric exercises, sprinting, classic power lifts, Olympic lifts and throwing sequence drills with overweight implements.

Progressive 'heavy' resistance training was emphasized during the first two training phases when performing all exercises (Hakkinen, 1989). During the strength conditioning phase, the athletes on average performed four sets of 8–10 repetitions at 60% of their one-repetition maximums for the various exercises. Training intensity increased to 1–4 sets of five repetitions at 85% of one-repetition maximums for the various exercises during the strength development phase. In summary, the sport-specific resistance training programme progressed from initially high-volume, low-intensity protocols towards low-volume, high-intensity protocols over the first 8 weeks.

During the strength–power phase, training intensity decreased slightly to 1–4 sets of eight repetitions at 80% of one-repetition maximums for the various exercises. Modifications to exercises included 3–5 sets of single repetitions of power lifts and Olympic lifts in which the weight was released at the end of the movement. Maximal single-repetition efforts during the medicine ball and plyometric exercises were also included. Progressive 'explosive-type' resistance training was the goal of this phase when performing all exercises (Hakkinen, 1989).

As the athletes progressed to the peaking and maintenance phase, exercises were limited to 3–5 repetitions of the classic power lifts and Olympic lifts at 80–90% of one-repetition maximums. The main emphasis in this phase was on improving neuromuscular coordination, as the athletes were training specifically to improve the technical aspects of the throwing motion to optimize athletic performance (Jones *et al.*, 1989).

Table 1. Characteristics of the participants (mean $\pm s$)

Variables	Group	Test session			
		1	2	3	4
Mass (kg)	Controls	70.0 ± 12.6	—	70.5 ± 12.7	—
	Athletes	96.8 ± 14.1	96.6 ± 13.7	96.6 ± 13.9	96.9 ± 13.8
Body composition (% fat)	Athletes	16.7 ± 5.70	16.2 ± 5.53	16.1 ± 5.14	15.8 ± 5.63
Overhead shot distance (m)	Athletes	14.3 ± 1.43	14.8 ± 1.65	15.2 ± 1.52	15.6 ± 1.52
Long jump distance (m)	Athletes	2.48 ± 0.29	2.55 ± 0.32	2.52 ± 0.28	2.58 ± 0.29
Vertical jump height (cm)	Athletes	9.17 ± 1.37	9.38 ± 1.57	9.67 ± 1.42	9.88 ± 1.30

Note: Performances by the athletes on the overhead shot, long jump and vertical jump were obtained from the coaches' practice records.

Apparatus

The right knee extensors were tested in a custom-made dynamometer (Edwards *et al.*, 1977; Koceja *et al.*, 1991). The participants sat on a straight-backed chair with their thighs supported by the seat, their pelvis secured by a seatbelt, their arms crossed over the chest, and their hips and knees flexed at 90°. Quadriceps force was measured by strapping the lower leg to an aluminium plate (26.7 × 5.08 × 1.27 cm) that was instrumented with an electromechanical load cell (Interface, Scottsdale, AZ; linear to 3 kN). The aluminium plate-load cell device was positioned just proximal to the malleoli. The torques developed during isometric knee extensions and twitch contractions were calculated from the forces sensed with the load cell and by measuring the distance, in metres, between the axis of the participant's knee and the load cell. The signal from the load cell was amplified and collected with an analog-to-digital (A/D) converter (Data Translation, Model 2801a, 1 kHz sampling rate) interfaced to a computer. Customized software was used for data acquisition and data analyses.

Electrical stimulation

Twitch contractions of the right knee extensors were evoked by percutaneous muscle stimulation. A pair of 8 × 12 cm pad electrodes treated with conducting gel was placed transversely over the right anterolateral thigh at the mid level. The mid-thigh level was determined as the equidistance between the inguinal crease and the base of the patella. The stimuli were square-wave voltage pulses of 2 ms duration delivered from an electrical stimulator (Teca Model M Stimulator, 0–300 volts output).

Measurement of voluntary isometric strength

At the onset of the protocol, three 100% MVC trials were recorded on a digital oscilloscope as 'warm-up' contractions. Each of the three trials consisted of a 2-s increase to maximum knee extension torque by isometrically contracting the right quadriceps muscle. Maximum torque was maintained for 2 s and then the participant was instructed to relax. A fourth trial was included if the peak torques on the first three 100% MVC trials differed by more than 5%. The peak torque obtained from the 'warm-up' MVC producing the maximal response was recorded.

Measurement of resting muscle twitches

Peak torque of a resting muscle twitch was evoked by delivering a single supramaximal stimulus to the relaxed quadriceps muscle. The use of a supramaximal stimulus ensured that the same constant fraction of the whole muscle was electrically activated on each trial (Bigland-Ritchie *et al.*, 1986). Three twitch contractions were collected with the A/D data-acquisition system. Twitch measurements were peak torque, contraction time (time to peak torque) and half-relaxation time. The measurements obtained from the twitch contraction evoking the maximal peak torque were used in the statistical analyses.

Measurement of voluntary activation of the quadriceps muscle during maximal isometric contractions

The interpolated twitch technique of Hales and Gandevia (1988) was used to measure the extent of voluntary activation of the quadriceps muscle during a 100% MVC. The participants were instructed to increase leg extensor torque gradually over 2 s to maximum and then, while holding this 100% MVC torque, a single supramaximal stimulus was delivered to the quadriceps muscle. The interpolated twitch method was repeated three times. There were approximately 60 s between maximal contractions. To encourage maximal efforts during each contraction, a target line was displayed on the oscilloscope that was 20% above the maximal peak torque of the 'warm-up' MVC. The participants also received verbal encouragement (normal tone of voice) to reach the target line.

The load cell was interfaced to a differential gain amplifier with a sample and hold circuit (Hales and Gandevia, 1988). When triggered, the sample and hold circuit measured the ongoing MVC torque or bias voltage. The bias voltage was then subtracted from the subsequent load cell signal to measure the interpolated twitch response at a gain of 20 and a resolution of 0.012 N · m. In practice, the resolution of the interpolated twitch amplitude is 1% of the amplitude of the resting muscle twitch due to biological fluctuations in muscle torque production. The two output channels from the differential gain amplifier with a sample and hold circuit were collected with the A/D data acquisition system (1 kHz sampling rate per channel).

The dependent variables were peak torque of the voluntary muscle contraction and peak torque, contraction time, half-relaxation time of the interpolated twitch response. The level of voluntary activation was calculated as $(((a - b)/a) \times 100)$, where a is the resting twitch torque and b is the interpolated twitch torque. Dependent variables obtained from the voluntary muscle contraction producing the maximal peak torque response were used in the statistical analyses.

Torque–time curve analyses and EMG recordings of rapid isometric MVC responses

The participants were instructed to reach maximum isometric torque as fast as possible, maintain maximum

torque for 2 s, and then relax. The participants performed the task three times with an inter-trial interval of 60 s. The EMG activity from the mid-belly of the right rectus femoris muscle was recorded with surface-recording electrodes (4 mm in diameter; bipolar electrode configuration). The torque response and EMG activity were collected with the A/D data-acquisition system. The sampling rate was 1 kHz per channel. The position of the recording electrodes with respect to the base of the patella was recorded to ensure similar electrode placement for each test session.

The dependent variables from the torque–time curve analyses were peak torque, contraction time and the average torque produced in 100 ms time periods from the onset of the torque production and overlapped by 50 ms (Hakkinen et al., 1985a). Contraction time was the interval between the onset of torque production and maximal torque production of the MVC response. Maximum integrated EMG (iEMG) and iEMG–time curve parameters were calculated from the EMG activity on each trial. The maximum iEMG value was calculated as the sum of EMG activity during the contraction time and expressed for 1 s. In the iEMG–time analysis, the iEMG values (expressed for 1 s) were calculated for the same 100 ms time periods that were used in the torque–time analysis. These iEMG data points reflected the pattern of neural drive. The dependent variables obtained from the rapid isometric contraction producing the maximal peak torque response were used in the statistical analyses.

Statistical analysis

A group by test session analysis of variance (ANOVA) was used to reveal neuromuscular adaptations in highly skilled athletes participating in a sport-specific resistance training programme. Because of the missing test sessions in the control group, a single-factor (test sessions) repeated-measures ANOVA was used to reveal the time-course of the neuromuscular adaptations in the highly skilled athletes. These analyses of variance incorporated the Newman-Keuls *post-hoc* test to detect progressive neuromuscular adaptations and Dunnett's *post-hoc* test to detect changes with respect to pre-training values. Statistical significance was set at $P < 0.05$.

Results

Resting muscle twitch, muscle strength and voluntary activation

Twitch torque, MVC torque and voluntary activation did not change between test sessions for the controls ($P > 0.05$). In the control group, the intra-class

reliability coefficients for these dependent variables between test sessions were 0.67, 0.95 and 0.95, respectively. Twitch torque (35.2 ± 11.8 *vs* 28.9 ± 8.96 N·m), contraction time (84.9 ± 9.99 *vs* 83.6 ± 9.53 ms) and half-relaxation time (64.3 ± 12.5 *vs* 59.4 ± 9.62 ms) of the resting muscle twitch were similar between the athletes and controls ($P > 0.05$). The contractile properties of the resting muscle twitch did not change with training in the athletes.

The MVC torque increased during the strength training programme as revealed by a significant test session main effect ($P < 0.05$; repeated-measures ANOVA) (Fig. 1a). Compared with pre-training, the athletes showed a significant 10% increase in MVC torque at test session 3 and a subsequent 15% increase at test session 4 ($P < 0.05$; Dunnett's *post-hoc* test). Voluntary activation of the quadriceps muscle did not change during the training programme ($P > 0.05$) (Fig. 1b).
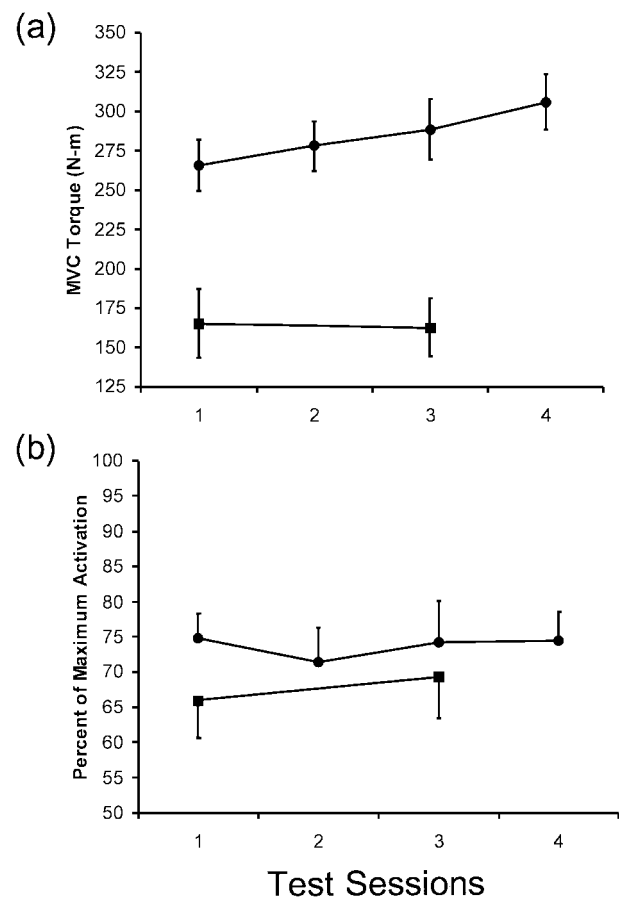

Fig. 1. Changes in isometric MVC torques (a) and voluntary activation values (b) for the athletes ($n = 14$) and the controls ($n = 8$) across test sessions. Error bars represent the standard errors of the means. ●, athletes; ■, controls.

Torque–time curve analyses and EMG recordings of rapid isometric MVC responses

Peak torque, maximal iEMG and contraction time did not change between test sessions for the controls ($P > 0.05$) (Fig. 2 and Table 2). In the controls, the intraclass reliability coefficients for these dependent variables between test sessions were 0.84, 0.64 and 0.87, respectively.

A significant group by test session interaction term was revealed for peak torque ($P < 0.05$) (Fig. 2a). In the trained athletes, peak torque increased by 12% from test session 1 to test session 2 ($P < 0.05$). Increases in peak torque from pre-training values were also observed in test sessions 3 (19%) and 4 (24%; $P < 0.05$). Peak torque for the athletes was greater than for the controls at each test session ($P < 0.05$).

The analysis of the simple main effects of test sessions revealed that increases in maximum iEMG were significant for the athletes but not for the controls
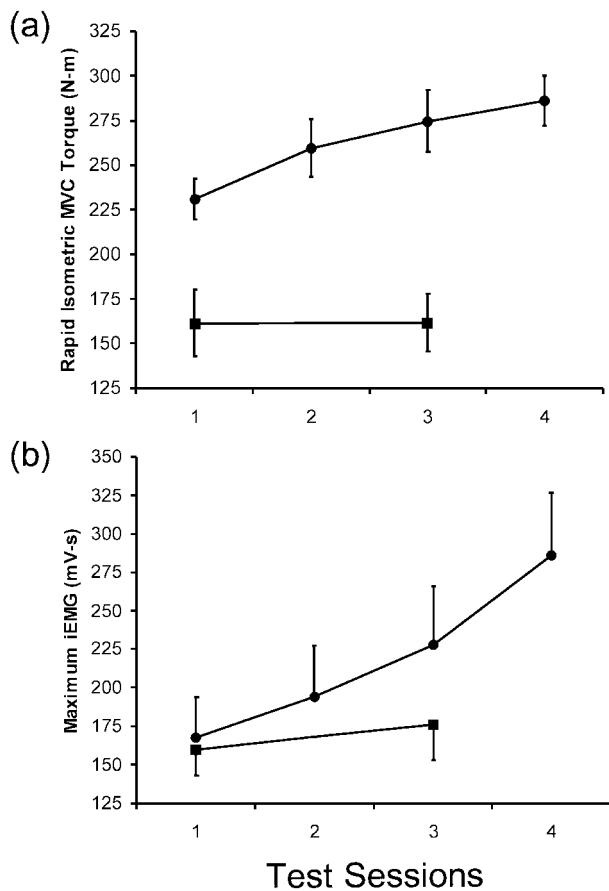
Table 2. Contraction times (ms) for the rapid isometric force development task across test sessions (mean $\pm$ s)

Test session	Trained athletes	Controls
1	355.1 ± 225.5	316.4 ± 92.28
2	335.1 ± 138.1	
3	392.9 ± 210.7	326.6 ± 78.30
4	384.9 ± 139.4	

(Fig. 2b). In the athletes, maximum iEMG increased by 71% from test session 1 to test session 4 ($P < 0.05$). Although maximum iEMG was similar in the two groups at test session 1, maximum iEMG was significantly greater in the athletes than in the controls at test session 4 ($P < 0.05$). The relationship between increases in peak MVC torque and increases in iEMG among the athletes was $r = 0.63$.

Contraction times were similar in the two groups across the test sessions (Table 2). However, significant group by test session by time period interaction terms ($P < 0.05$) were revealed for averaged torques (Fig. 3) and averaged iEMG values (Fig. 4). Averaged torques and averaged iEMG values by time periods were similar for the two test sessions in the controls ($P > 0.05$) (Figs 3b and 4b). The average amounts of torque produced by the athletes between 200 and 400 ms after the onset of the isometric contraction were significantly greater during test sessions 2, 3 and 4 than pre-training ($P < 0.05$) (Fig. 3a). In addition, the average amounts of iEMG generated by these athletes between 100 and 200 ms after the onset of the isometric contraction were significantly greater during test session 4 than during the other three test sessions ($P < 0.05$) (Fig. 4a).

Evaluation of athletic performance

Ten of the athletes participated in NCAA championship meets. Thirteen All-American Honors and nine conference championships were earned by the athletes. One American record and one World record were set by the athletes. These results demonstrated that this pre-season training regimen induced the appropriate neuromuscular adaptations necessary for successful throwing performance.

In addition, performances of the overhead shot, long jump and vertical jump improved from test session 1 to test session 4 by 9%, 4% and 8%, respectively ($P < 0.05$) (Table 1). There were moderate relationships between increases in laboratory-based strength measurements and performance improvements for the overhead shot distance ($r = 0.60$), long jump distance ($r = 0.52$) and vertical jump height ($r = 0.61$).
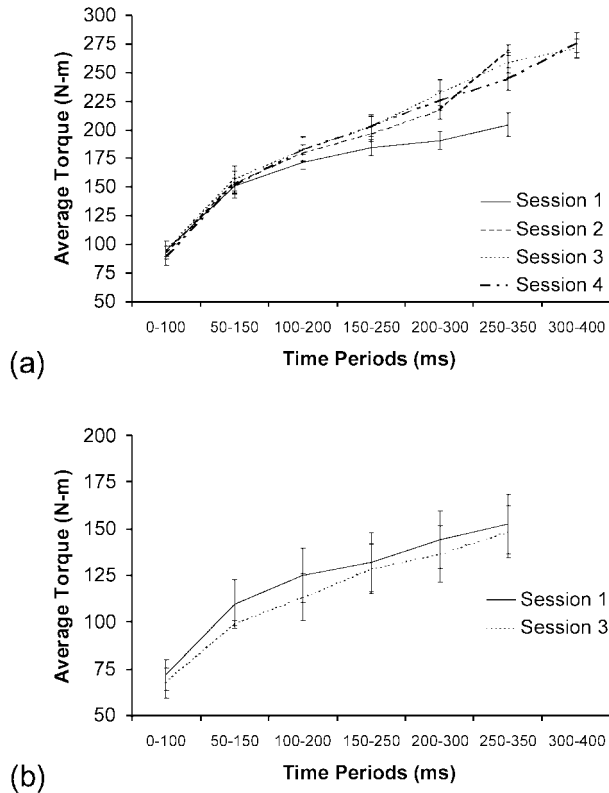

Fig. 2. Changes in peak MVC torques (a) and maximum iEMG values (b) during rapid isometric contractions at maximal effort for the athletes and the controls across test sessions. Error bars represent the standard errors of the means. ●, athletes; ■, controls.

(a)

(b)

Fig. 3. The rate of maximum force production in each test session for the athletes (a) and the controls (b). Rate of maximum force production represents the average torque calculated in 100 ms time periods from the onset of force production and overlapped by 50 ms. The normalization of the force–time curve across test sessions is in the time domain to differentiate between improvements in maximal strength (high force portions of the absolute force–time curve) and rapid force production (early parts of the absolute force–time curve) (cf. Hakkinen, 1989). Error bars represent the standard errors of the means.

Fig. 4. The pattern of neural drive in each test session for the athletes (a) and the controls (b). Pattern of neural drive represents the iEMG values, expressed for 1 s, in each 100 ms time period from the onset of force production and overlapped by 50 ms. The normalization of the iEMG–time curve across test sessions is in the time domain to differentiate between improvements in maximal muscle activation (late part of the iEMG–time curve) and muscle recruitment patterns during rapid movements (early parts of the iEMG–time curve) (cf. Hakkinen, 1989; iEMG expressed in absolute units). Error bars represent the standard errors of the means.

Discussion

The sport-specific resistance training programme improved the maximality of neural drive during rapid isometric contractions, as indicated by the positive relationship between increases in MVC torques and increases in iEMG ($r = 0.63$). Specific to the peaking and maintenance phase, improvements to the pattern of neural drive were made evident by increases in EMG amplitudes at the onset of rapid isometric contractions. These results cannot exclude the possibility that other training regimens would produce similar results. The results also do not exclude the possibility that muscular adaptations contributed to strength gains and improved athletic performance. However, muscle twitch torques were unaffected, which tentatively suggests that neural adaptations were the predominant underlying mechan-
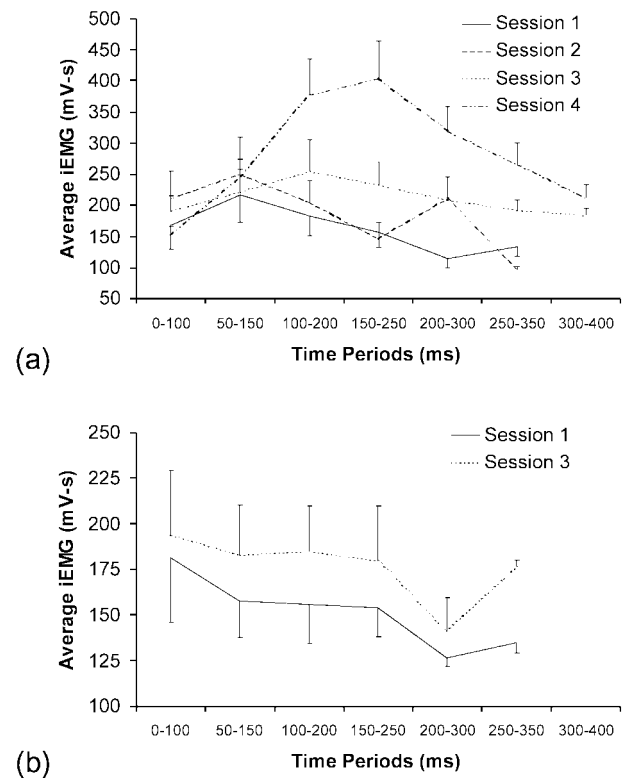
isms for the laboratory-based strength gains in these highly skilled athletes.

Most studies using the interpolated twitch technique to measure voluntary activation of the quadriceps muscle have reported values between 90% and 100% (cf. Behm and St. Pierre, 1998). Voluntary activation values of 72%, on average, probably represented potentiation bias during the MVC that was easily detected with a sensitive twitch interpolation technique. Twitch torque potentiation during the MVC would cause an underestimation of the 'true' extent of voluntary activation (Belanger and McComas, 1981; Bulow *et al.*, 1993). Voluntary activation of the quadriceps muscle was $83.0 \pm 9.1\%$ in healthy adults even when using a MVC lasting 10 s to measure post-activation potentiation of the resting muscle twitch (Hamada *et al.*, 2000). Voluntary activation of the quadriceps muscle was between 85% and 90% in both

healthy controls and elite male volleyball players in the study of Huber *et al.* (1998). Sport-specific resistance training did not induce increases in voluntary activation of the quadriceps muscle in our highly skilled athletes. This finding is in agreement with previous research on progressive resistance training in initially untrained individuals and in strength-trained athletes during taper procedures (Carolan and Cafarelli, 1992; Gibala *et al.*, 1994; Behm and St. Pierre, 1998; Herbert *et al.*, 1998).

There are inherently different underlying motor control strategies for measuring neuromuscular performance during sustained MVC contractions and rapid MVC contractions. Torque–iEMG analyses of rapid isometric contractions at maximal effort provide additional insights on the voluntary activation of the agonist motoneuron pool, because of the limited capacity of the motor system to fully activate a muscle in a short time (Enoka, 1983; Gottlieb *et al.*, 1989; Suzuki *et al.*, 1994). The positive relationship between increases in MVC torques and increases in iEMG ($r = 0.63$) during the rapid isometric MVC task suggested that improvements to the maximality of neural drive may have occurred during the course of this sport-specific resistance training programme.

Improvements to the pattern of neural drive may manifest as increased motor unit synchronization (Enoka, 1997). Although the evidence is not definitive, the hypothesis that increased motor unit synchronization occurs with strength training is still tenable (Sale, 1988; Moritani, 1993; Enoka, 1997). Increasing motor unit synchronization and motor unit discharge rates are neural factors that contribute to increased surface-recorded EMG amplitude (Jones *et al.*, 1989; Moritani, 1993; Kamen and Knight, 1999; Yao *et al.*, 2000). The 71% increase in surface EMG amplitude is consistent with the effects of a moderate amount of motor unit synchronization on reducing the cancellation of action potentials within the surface EMG signal (Yao *et al.*, 2000). The training-induced increase in the averaged iEMG response at the onset of a rapid MVC may reflect a change in the motor unit recruitment pattern – for example, increased synchronization or increased 'doublets' firing. Alterations in the motor unit recruitment pattern may improve the neuromuscular coordination underlying the technical aspects of athletic skill performance without a corresponding shift in the isometric torque–time curve. [For a discussion of the functional significance of motor unit synchronization on isometric force, see Yao *et al.* (2000). For a discussion of the functional significance of motor unit activation patterns on the speed of voluntary muscle contractions, see Van Cutsem *et al.* (1998).]

The observed increases in iEMG may be peripheral in origin (Jones *et al.*, 1989; Narici *et al.*, 1989; Herbert *et al.*, 1998). However, the concomitant increases in iEMG and MVC torque suggest that 16 weeks of sport-specific resistance training induces adaptations to neural drive. Previous research indicated that the magnitudes of strength adaptations for highly trained athletes were approximately 5% on average (Hakkinen *et al.*, 1987, 1988, 1991; Hakkinen and Pakarinen, 1991; Gibala *et al.*, 1994; Hakkinen and Kallinen, 1994). The magnitudes of strength adaptations observed in this research, 15% and 24%, were similar to values reported for individuals without a prolonged background in strength training (e.g. Narici *et al.*, 1989; Yue and Cole, 1992; Herbert *et al.*, 1998; Knight *et al.*, 1998; Akima *et al.*, 1999). Neural adaptations are considered to be the underlying mechanisms for the rapid strength gains in untrained individuals and for periodic strength gains in well-trained athletes, in whom the contributions of muscle hypertrophy may already be maximized (Enoka, 1988, 1997; Hakkinen, 1989; Jones *et al.*, 1989; Hakkinen and Kallinen, 1994; Kramer *et al.*, 1998; Sale, 1988). In addition, the transfer of performance improvements among the laboratory-based strength tasks and measurements of the overhead shot distance, long jump distance and vertical jump height, as well as the high athletic achievement, inferred that the sport-specific resistance training programme induced a motor learning adaptation (Jones *et al.*, 1989; Enoka, 1997). The reliability of iEMG values between sessions for the controls indicated that the EMG recording environment was consistent across days.

The strength development phase induced the expected increase to the high torque portion, greater than 200 ms, of the isometric torque–time curve (Hakkinen *et al.*, 1985a). An increase in musculotendinous stiffness after 4 weeks of progressive heavy resistance exercise may explain the increase in torque per unit time in the absence of increased iEMG (Pousson *et al.*, 1990; Narici *et al.*, 1996). There was no subsequent increase in the high-velocity portion, less than 200 ms, of the isometric torque–time curve after either the strength–power phase or the peaking and maintenance phase (Hakkinen *et al.*, 1985b). Adaptations in the high-velocity portion of the isometric force–time curve depend upon an explosive type strength-training stimulus (Hakkinen, 1989). The hybrid nature or the short duration of the strength–power phase may not have provided our athletes with the most appropriate training stimulus to induce this adaptation.

In conclusion, our results support the hypothesis that sport-specific resistance training induces neural adaptations to the pattern of neural drive in highly skilled athletes. Although the sport-specific training programme did not increase voluntary activation of the quadriceps muscle during a sustained MVC task, improvements to the maximality of neural drive may

occur when the motor system is required to fully activate a muscle in a short time.

Acknowledgements

References

Akima, H., Takahashi, H., Kuno, S.Y., Masuda, K., Masuda, T., Shimojo, H., Anno, I., Itai, Y. and Katsuta, S. (1999). Early phase adaptations of muscle use and strength to isokinetic training. *Medicine and Science in Sports and Exercise*, **31**, 588–594.

Allen, G.M., Gandevia, S.C. and McKenzie, D.K. (1995). Reliability of measurements of muscle strength and voluntary activation using twitch interpolation. *Muscle and Nerve*, **18**, 593–600.

Behm, D.G. and St. Pierre, D.M. (1998). The effects of strength training and disuse on the mechanisms of fatigue. *Sports Medicine*, **25**, 173–189.

Belanger, A.Y. and McComas, A.J. (1981). Extent of motor unit activation during effort. *Journal of Applied Physiology*, **51**, 1131–1135.

Bigland-Ritchie, B., Furbush, F. and Woods, J.J. (1986). Fatigue of intermittent submaximal voluntary contractions: central and peripheral factors. *Journal of Applied Physiology*, **61**, 421–429.

Bulow, P.M., Norregaard, J., Danneskiold-Samsoe, B. and Mehlsen, J. (1993). Twitch interpolation technique in testing of maximal muscle strength: influence of potentiation, force level, stimulus intensity and preload. *European Journal of Applied Physiology*, **67**, 462–466.

Carolan, B. and Cafarelli, E. (1992). Adaptations in coactivation after isometric resistance training. *Journal of Applied Physiology*, **73**, 911–917.

Edwards, R.H., Young, A., Hosking, G.P. and Jones, D.A. (1977). Human skeletal muscle function: description of tests and normal values. *Clinical Science and Molecular Medicine*, **52**, 283–290.

Enoka, R.M. (1983). Muscular control of a learned movement: the speed control system hypothesis. *Experimental Brain Research*, **51**, 135–145.

Enoka, R.M. (1988). Muscle strength and its development: new perspectives. *Sports Medicine*, **6**, 146–168.

Enoka, R.M. (1997). Neural adaptations with chronic physical activity. *Journal of Biomechanics*, **30**, 447–455.

Gibala, M.J., MacDougall, J.D. and Sale, D.G. (1994). The effects of tapering on strength performance in trained athletes. *International Journal of Sports Medicine*, **15**, 492–497.

Gottlieb, G.L., Corcos, D.M. and Agarwal, G.C. (1989). Organizing principles for single-joint movements. I. A speed-insensitive strategy. *Journal of Neurophysiology*, **62**, 342–357.

Hakkinen, K. (1989). Neuromuscular and hormonal adaptations during strength and power training: a review. *Journal of Sports Medicine and Physical Fitness*, **29**, 9–26.

Hakkinen, K. and Kallinen, M. (1994). Distribution of strength training volume into one or two daily sessions and neuromuscular adaptations in female athletes. *Electromyography and Clinical Neurophysiology*, **34**, 117–124.

Hakkinen, K. and Pakarinen, A. (1991). Serum hormones in male strength athletes during intensive short term strength training. *European Journal of Applied Physiology*, **63**, 194–199.

Hakkinen, K., Alen, M. and Komi, P.V. (1985a). Changes in isometric force- and relaxation-time, electromyographic and muscle fiber characteristics of human skeletal muscle during strength training and detraining. *Acta Physiologica Scandinavica*, **125**, 573–585.

Hakkinen, K., Komi, P.V. and Alen, M. (1985b). Effect of explosive type strength training on isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of leg extensor muscles. *Acta Physiologica Scandinavica*, **125**, 587–600.

Hakkinen, K., Komi, P.V., Alen, M. and Kauhanen, H. (1987). EMG, muscle fibre and force production characteristics during a 1 year training period in elite weightlifters. *European Journal of Applied Physiology*, **56**, 419–427.

Hakkinen, K., Pakarinen, A., Alen, M., Kauhanen, H. and Komi, P.V. (1988). Neuromuscular and hormonal adaptations in athletes to strength training in two years. *Journal of Applied Physiology*, **65**, 2406–2412.

Hakkinen, K., Kallinen, M., Komi, P.V. and Kauhanen, H. (1991). Neuromuscular adaptations during short-term 'normal' and reduced training periods in strength athletes. *Electromyography and Clinical Neurophysiology*, **31**, 35–42.

Hales, J.P. and Gandevia, S.C. (1988). Assessment of maximal voluntary contraction with twitch interpolation: an instrument to measure twitch responses. *Journal of Neuroscience Methods*, **25**, 97–102.

Hamada, T., Sale, D.G., MacDougall, J.D. and Tarnopolsky, M.A. (2000). Postactivation potentiation, fiber type, and twitch contraction time in human knee extensor muscles. *Journal of Applied Physiology*, **88**, 2131–2137.

Herbert, R.D., Dean, C. and Gandevia, S.C. (1998). Effects of real and imagined training on voluntary muscle activation during maximal isometric contractions. *Acta Physiologica Scandinavica*, **163**, 361–368.

Huber, A., Suter, E. and Herzog, W. (1998). Inhibition of the quadriceps muscles in elite male volleyball players. *Journal of Sports Sciences*, **16**, 281–289.

Jones, D.A., Rutherford, O.M. and Parker, D.F. (1989). Physiological changes in skeletal muscle as a result of strength training. *Quarterly Journal of Experimental Physiology*, **74**, 233–256.

Judge, L.W. (1992). Preseason preparation for the collegiate shot putter. *National Strength and Conditioning Association Journal*, **14**, 20–26.

Kamen, G. and Knight, C.A. (1999). The relationship between maximal motor unit firing rate and surface-recorded EMG amplitude in young and older adults. In *Proceedings of the Fifth International Brain Research Organization World Congress of Neuroscience*, p. 67. Paris: IBRO.

Kamen, G., Knight, C.A., Laroche, D.P. and Asermely, D.G. (1998). Resistance training increases vastus lateralis motor unit firing rates in young and older adults. *Medicine and Science in Sports and Exercise*, **30**(suppl. 5), S337.

Knight, C.A., Kamen, G. and Burke, J.R. (1998). Increased motor unit activation in young and older adults following resistance exercise training. *Medicine and Science in Sports and Exercise*, **30**(suppl. 5), S336.

Koceja, D.M., Bernacki, R.H. and Kamen, G. (1991). Methodology for the quantitative assessment of human crossed-spinal reflex pathways. *Medical and Biological Engineering and Computing*, **29**, 603–606.

Kramer, W.J., Duncan, N.D. and Volek, J.S. (1998). Resistance training and elite athletes: adaptations and programme considerations. *Journal of Orthopaedic and Sports Physical Therapy*, **28**, 110–119.

Moritani, T. (1993). Neuromuscular adaptations during the acquisition of muscle strength, power and motor tasks. *Journal of Biomechanics*, **26**(suppl. 1), 95–107.

Narici, M.V., Roi, G.S., Landoni, L., Minetti, A.E. and Cerretelli, P. (1989). Changes in force, cross-sectional area and neural activation during strength training and detraining of the human quadriceps. *European Journal of Applied Physiology*, **59**, 310–319.

Narici, M.V., Hoppeler, H., Kayser, B., Landoni, L., Claassen, H., Gavardi, C., Conti, M. and Cerretelli, P. (1996). Human quadriceps cross-sectional area, torque and neural activation during 6 months strength training. *Acta Physiologica Scandinavica*, **157**, 175–186.

Pousson, M., van Hoecke, J. and Goubel, F. (1990). Changes in elastic characteristics of human muscle induced by eccentric exercise. *Journal of Biomechanics*, **23**, 343–348.

Sale, D.G. (1988). Neural adaptation to resistance training. *Medicine and Science in Sports and Exercise*, **20**, S135–S145.

Suzuki, M., Yamazaki, Y. and Matsunami, K. (1994). Relationship between force and electromyographic activity during rapid isometric contraction in power grip. *Electroencephalography and Clinical Neurophysiology*, **93**, 218–224.

Van Cutsem, M., Duchateau, J. and Hainaut, K. (1998). Changes in single motor unit behaviour contribute to the increase in contraction speed after dynamic training in humans. *Journal of Physiology (London)*, **513** (Part 1), 295–305.

Yao, W., Fuglevand, R.J. and Enoka, R.M. (2000). Motor-unit synchronization increases EMG amplitude and decreases force steadiness of simulated contractions. *Journal of Neurophysiology*, **83**, 441–452.

Yue, G. and Cole, K.J. (1992). Strength increases from the motor programme: comparison of training with maximal voluntary and imagined muscle contractions. *Journal of Neurophysiology*, **67**, 1114–1123.