Eur J Appl Physiol (1986) 55:147–155

European Journal of
Applied Physiology
and Occupational Physiology

Training-induced changes in neuromuscular performance under voluntary and reflex conditions

Keijo Häkkinen and Paavo V. Komi

Department of Biology of Physical Activity, University of Jyväskylä, SF-40100 Jyväskylä, Finland

Summary. To investigate training-induced changes in neuromuscular performance under voluntary and reflex contractions, 11 male subjects went through heavy resistance (high loads of 70–120% of one maximum repetition) and 10 male subjects through explosive type (low loads with high contraction velocities) strength training three times a week for 24 weeks. A large increase (13.9%, $p < 0.01$) in voluntary unilateral maximal knee extension strength with only slight and insignificant changes in time of isometric force production were observed during heavy resistance strength training. Explosive type strength training resulted in a small insignificant increase in maximal strength but in considerable shortening ($p < 0.05$) in the time of force production. A significant increase ($p < 0.05$) noted in the averaged maximal integrated electromyogram (IEMG) of the knee extensors during heavy resistance strength training correlated ($p < 0.01$) with the increase in maximal strength. No changes were noted during training in reflex time components, but significant decreases ($p < 0.05$) occurred in the peak-to-peak amplitudes of the reflex electromyograms (EMG) in both groups. The individual changes during training in the reflex EMG/force ratio were related ($p < 0.01$) to the respective changes in IEMG/force ratio in voluntary contractions. The present observations support the concept of specificity of training, and suggest that specific training-induced adaptations in the neuromuscular system may be responsible for these changes in performance.

Key words: Neuromuscular performance — Training — Adaptation

Offprint requests to: K. Häkkinen at the above address

Introduction

Specificity of training-induced changes in neuromuscular performance demonstrable by increases in maximal strength, in isometric force-time and in force-velocity curves is well documented (e.g., Ikai 1970; Häkkinen et al. 1980; 1981; Caiozzo et al. 1981; Komi et al. 1982). While differences in the magnitudes of these improvements may result from different training stimuli, recent experiments have concentrated on the examination of specific neural and muscular adaptations in the neuromuscular system responsible for the increased performance (e.g., MacDougall et al. 1977; Moritani and DeVries 1979; Coyle et al. 1981; Komi et al. 1978; 1982; Häkkinen et al. 1981; 1985a, b; Häkkinen and Komi 1983a, b). The magnitudes and time courses of these specific adaptations in various components of the neuromuscular system during training may vary, due to the type and/or intensity of training and especially due to the duration of specific training (Häkkinen et al. 1985a, b). In addition to training-induced adaptations in voluntary contraction, some documented data are available to demonstrate that training effects may also take place in reflex responsiveness (e.g., Milner-Brown et al. 1975; Sale et al. 1979; 1982; Häkkinen and Komi 1983b).

The purpose of the present investigation was to examine long-term heavy resistance and explosive type strength training-induced effects on electromyographic and force production characteristics of human skeletal muscle in voluntary and reflex contraction, with special regard to their possible interrelationships. The measurements were also administered after the termination of these two types of training to examine possible detraining effects. The present study was an extension based on analyses of some measurements performed simultaneously during our previous training experiments (Häkkinen et al. 1985a, b, c).

Methods

Subjects. The experimental subjects of the study were 21 males who had experience in weight training, divided into two groups, A ($n = 11$) and B ($n = 10$). The control subjects were 8 physically active males who also had had experience in weight training. These three groups were comparable in terms of their normal daily activities. Table 1 describes the physical characteristics of the subject groups. The results obtained with these subjects from bilateral isometric force measurements (Häkkinen et al. 1985a, b) and from hormonal analyses (Häkkinen et al. 1985c) have been reported elsewhere. The present paper describes analyses of unilateral measurements performed under both voluntary and reflex conditions.

Training. Supervised training of the two experimental groups lasted for 24 weeks and was followed by a 12-week detraining period, the total duration therefore being 36 weeks. The control subjects maintained their normal physical activities throughout the total experimental period, but did not participate in the controlled training procedure.

Group A participated in heavy resistance strength training. The training of the leg extensor muscles, performed with barbells three times a week, consisted of a dynamic squat lift exercise, in which the subject squatted with a loaded barbell on the shoulders. During any one training session 18—30 lifts were performed. These training lifts also included periodically a few contractions which were performed only eccentrically. The load on the barbell in the squat lifts ranged between 70 and 120% of one maximum (concentric) repetition (1—10 repetitions per set). To prevent injuries and make the training program more interesting, light (60—80% of one maximum repetition) concentric exercises for the trunk, arms and legs were also included in each training session. During the detraining period no strength training was undertaken, but the subjects maintained their normal daily activities.

Group B participated in progressive explosive strength training by performing various vertical jumps (100—200 jumps per training session) with maximal effort. The vertical jumps performed were: 1) a counter movement jump with a loaded barbell on the shoulders (of 10—60% of one maximum repetition), 2) a standing five jump, 3) hurdle jumps with five hurdles, 4) drop jumps (from dropping heights of 30—60 cm) followed by immediate rebounds and 5) drop jumps in which the body weight was reduced during the contact phase with the help of rubber bands (see Häkkinen et al. 1985b). Group B also undertook the light concentric strengthening exercises (60—80% of one maximum repetition) for trunk, arms and legs practiced by group A. During detraining group B ceased controlled training but maintained their normal daily activities.

Measurements

Both experimental groups were tested on four identical occasions at twelve week intervals before, during and after the 36-week experimental period. The controls participated only in the pre- and post-training measurements.

A dynamometer (Komi et al. 1979) was used to measure the maximal unilateral isometric force and various force-time parameters of the right knee extensors. After a few warm-up and familiarization contractions on the dynamometer the subjects performed three to six maximal isometric contractions at knee and hip angles of 90° and 110°, respectively. These contractions were performed at the maximal rate of force development. The force in each contraction was recorded on magnetic tape (Racal Store 7) and analyzed with a HP 1000F computer system. In the force-time analysis (Häkkinen et al. 1980), the times needed to increase the force on the relative scale from 10 per cent of maximum to 30, 60 and 90% were calculated. On the absolute scale, the corresponding calculations were performed from the level of 20 N to 100, 200, 300, 400, 500 and 600 N. The relaxation-time curve was analyzed in the relaxation with a starting force level of 85% (Viitasalo et al. 1980), and the times needed to relax to 60, 30 and 10% were calculated.

Electromyographic activity (EMG) was recorded from the right rectus femoris (RF), vastus lateralis (VL), and vastus medialis (VM) during both maximal and several submaximal contractions and also during reflex contractions. The submaximal contractions were registered after the maximal contractions in random order at 20% intervals and the required force level was maintained for 2.5 s. Bipolar (20-mm interelectrode distance) surface EMG recording (Beckman miniature-sized skin electrodes) was employed, and the electrodes were placed longitudinally on the motor-point area as determined by a Neuroton 626 stimulator. The positions of the electrodes were tattooed on the skin with small ink dots (see Häkkinen and Komi 1983a). These dots ensured the same electrode positioning for each test during the 36-week experimental period. After amplification with Brookdeal 9432 preamplifiers (60 dB, 1—1000 Hz) the EMGs were stored simultaneously with the force and time signals on magnetic tape (Racal Store 7). EMG was integrated (IEMG for 1 s) for each muscle separately with an HP 1000F computer system, and was later averaged for further analyses. In the IEMG-time analysis, EMG was integrated (expressed also for 1 s) for 9 consecutive time periods of 100 ms from the start of the contraction (0—100, 50—150, 100—200, 150—250, 200—300, 250—350, 300—400, 350—450 and 400—500 ms). The patellar reflexes of the right leg were measured on the dynamometer used for the voluntary contractions. The subject was in a seated position, relaxed and kept his eyes closed. The reflex hammer (see Viitasalo et al. 1980, Häkkinen and Komi 1983b) was dropped from an angle of 90 degrees with respect to the patellar tendon. The tap to the tendon was sensed by a microswitch embedded in the hammer. The force produced during these reflex contractions in the isometric condition was recorded and stored on magnetic tape simultaneously with the microswitch signal, the EMGs, and a timing signal of 1000 Hz. EMG and force signals were later played back on a graphic recorded with a $\times 16$ speed reduction. The total reflex time was divided into reflex latency (LAT) and reflex electromechanical delay (EMD) using thresholds of 0.010 mV and 1 N for EMG and force respectively. EMGs and force were analyzed also for their peak-to-peak amplitudes. For each EMG parameter the average of the values for the three muscles was calculated. The reading accuracy of the graph papers for time was 1 ms, for EMG amplitude 0.5 mm (1 mm = 0.010 mV), and for reflex force 1 N. The reflex responses were analyzed if the peak-to-peak amplitude of force had reached the level of 10 N. For each reflex parameter the average of two reflexes was used for further analyses.

Means, standard errors, and coefficients of correlation were calculated by standard methods. Differences between values before and after training, and separately after training and detraining, were tested for significance by the paired Student's t-test. The level of significance was set at 0.05.

Table 1. Physical characteristics of group A (heavy resistance strength training) and group B (explosive type strength training) before and after 24 weeks of training and after the subsequent 12-week detraining. The corresponding values for the control group are also shown

Variable		Before training		After training		After detraining	
		Mean	SD	Mean	SD	Mean	SD
Age (year)	Group A	25.6	4.3	—		—	
	Group B	27.1	3.2	—		—	
	Control	27.6	5.1	—		—	
Height (cm)	Group A	178.5	6.7	—		—	
	Group B	176.3	5.4	—		—	
	Control	179.7	3.7	—		—	
Mass (kg)	Group A	77.4	6.9	78.5*	6.0	78.9	6.3
	Group B	74.7	9.6	74.3	9.5	75.1	10.4
	Control	75.6	8.2	75.8	7.8	—	

$* = p < 0.5$

Results

As reported earlier (Häkkinen et al. 1985a, b, c) 24 weeks of heavy resistance strength training resulted in a significant ($p < 0.05$) increase in weight (Table 1), and other characteristics describing that body mass increased while no significant changes were noted in group B or in the control group.

Unilateral isometric force, force- and relaxation-times

The voluntary unilateral isometric knee extension force increased during the 24-week in group A from 733±201 to 835±215 N (Table 2 and Fig. 1), corresponding to an average increase of 13.9% ($p < 0.01$). During the subsequent 12-week detraining period the force decreased ($p < 0.05$) to 781±200 N. No statistically significant changes were noted during the experimental period in this variable in group B or in the control group. The average force-time curve changed in the absolute scale during training in group A so that the times to reach higher force levels decreased slightly (ns.) (Table 2 and Fig. 2). In the relative scale slight (ns.) increases of force production times were noted. In group B the times to reach force levels decreased both in the absolute and relative scales during the training, the time to reach a 30% force level decreasing significantly. During detraining the times to reach the absolute force levels decreased ($p < 0.05$) in group A while slight (ns.) lengthening in times of force production both in the absolute and relative scales was noted in group B. No statistically significant changes were noted during the experimental period in the force-times in the control group. No significant changes were noted in the relaxation-times during the experimental period in groups A and B or in the control group (Table 2).

Maximal average IEMG and IEMG-force curves

An increase in the averaged maximal IEMG of the knee extensors in group A from 0.27±0.08 to

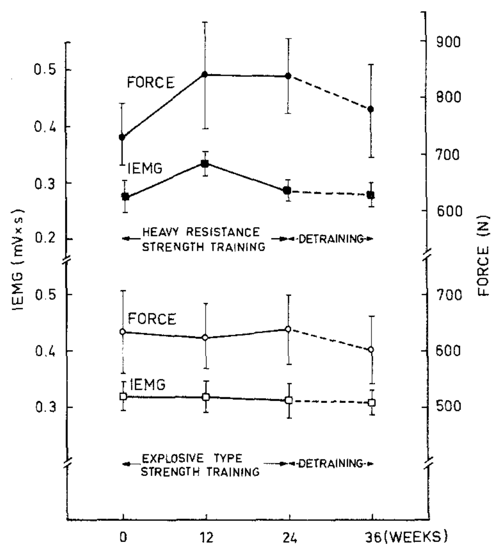

Fig. 1. Mean (±SE) unilateral knee extension isometric force and integrated electrical activity (IEMG averaged for vastus medialis, vastus lateralis and rectus femoris) during the heavy resistance and explosive type strength training of the two experimental groups, and after detraining

Table 2. Voluntary unilateral isometric force, maximal average IEMG and selected isometric force-time and relaxation-time characteristics of the knee extensors for group A (heavy resistance strength training) and group B (explosive type strength training) before and after the 24 weeks of training and after the subsequent 12-week detraining, and for the control group

Variable		Before training		After training		After detraining	
		Mean	SD	Mean	SD	Mean	SD
Voluntary unilateral isometric force (N)	Group A	733	201	835*	215	781*	250
	Group B	633	216	640	184	603	180
	Control	644	157	648	112	—	
Maximal average IEMG (RF, VL, VM) ($mV \cdot s^{-1}$)	Group A	0.27	0.08	0.29	0.05	0.28	0.06
	Group B	0.34	0.09	0.34	0.16	0.34	0.13
	Control	0.39	0.11	0.38	0.13	—	
Force-times (ms) 100 N	Group A	32.0	8.0	33.2	8.9	32.6	9.6
	Group B	30.9	9.5	29.4	9.2	32.0	9.9
	Control	30.7	7.3	35.4	12.1	—	
500 N	Group A	166.7	55.8	148.0	49.8	163.0	62.3
	Group B	161.1	47.5	151.6	56.7	188.0	104.4
	Control	165.8	42.3	251.9	126.7	—	
30%	Group A	39.3	14.3	43.4	19.6	35.9*	16.4
	Group B	33.3	4.3	29.9*	4.0	31.6	7.7
	Control	37.6	11.5	41.9	17.6	—	
60%	Group A	113.6	34.7	136.9	58.1	110.8*	39.8
	Group B	98.2	22.4	90.2	18.3	100.2	36.6
	Control	98.1	32.1	128.1	50.0	—	
90%	Group A	502.5	377.7	528.6	266.0	538.4	276.5
	Group B	544.9	398.0	328.6	232.0	464.1	413.0
	Control	483.0	466.0	615.2	406.0	—	
Relaxation-time (ms) 85%→10%	Group A	137.6	94.9	142.8	89.0	121.2	40.0
	Group B	91.1	45.4	122.0	30.0	122.0	47.8
	Control	145.7	68.1	156.5	41.4	—	

$* = p < 0.05$ $** = p < 0.01$

0.33 ± 0.06 $mV \cdot s^{-1}$ ($p < 0.05$) was observed after 12 weeks of training while after the 24-week training this value was 0.29 ± 0.05 $mV \cdot s^{-1}$ (Fig. 1 and Table 2). During the detraining a slight (ns.) decrease down to 0.28 ± 0.06 $mV \cdot s^{-1}$ was noted in this variable. In group B and in the control group no significant changes were noted during the experimental period in the averaged IEMG of the knee extensors. The individual changes in maximum IEMG and in maximal force correlated significantly in both experimental groups both dur-

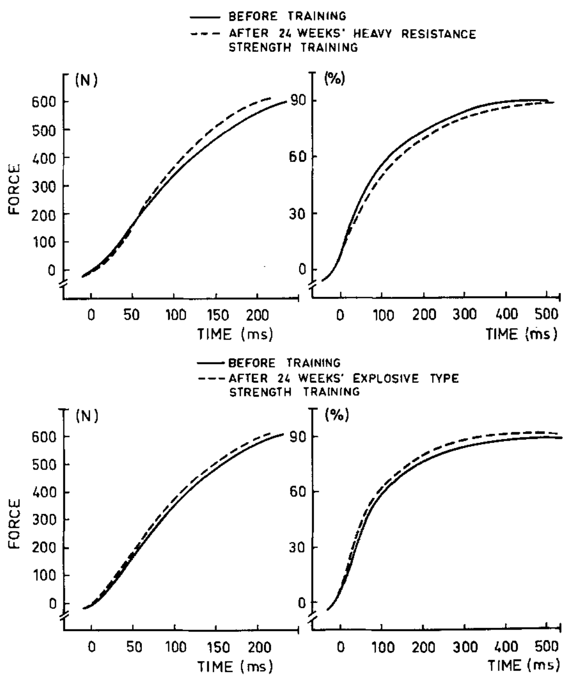

Fig. 2. Average unilateral isometric force-time curves of the knee extensors in both the absolute and relative scales before and after the heavy resistance and explosive type strength training of the two experimental groups. The absolute forces are analyzed as a function of time up to a force level of 600 N and the relative forces up to a force level of 90 per cent: the curves of absolute force do not therefore show the change in maximal force (see Table 2)

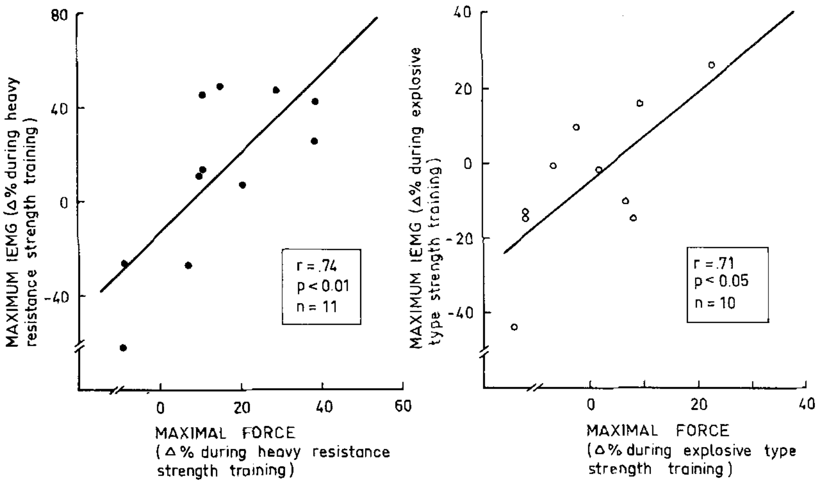

Fig. 3. Relationships between the relative changes in maximal integrated electrical activity (maximum IEMG) (IEMG averaged for the three superficial knee extensors) and in maximal force of unilateral isometric knee extension after the heavy resistance and explosive type strength training of the two experimental groups

ing training ($r=0.74, p<0.01$ and $r=0.71, p<0.05$ for group A and B, respectively, Fig. 3) and during detraining ($r=0.62$, $p<0.01$ for all subjects). No significant changes were observed in the relationship between the averaged IEMG and muscle force from submaximal to maximal force levels during the training in either group A or group B. A slight shifting (ns.) in this IEMG/force curve to the right was, however, noted at all examined force levels in both groups. In the control group, no changes occurred in the IEMG/force curve.

Average IEMG-time curve

The average IEMG/time curve shifted slightly but insignificantly upwards in group A during the first 12 weeks of training but only two periods (5 and 7) showed significant ($p<0.05$) increases in mean IEMG. The average IEMG/time curve shifted (ns.) downwards during the latter half of the training period: only minor (ns.) changes were observed in this curve during detraining. In group B, the IEMG/time curve shifted slightly (ns.) upwards throughout the 24-week training period, and during detraining this shift was reversed. In the control group no significant shifts in IEMG/time curves were noted.

Reflex characteristics

No significant changes were noted in groups A and B in reflex latency (LAT) during the training or detraining periods (Table 3 and Fig. 4). The same was true for electromechanical delay (EMD) (Table 3 and Fig. 4). The peak-to-peak amplitudes of the reflex EMG decreased significantly ($p<0.05$) during the training of both experimental groups A and B (Table 3 and Fig. 5). During the training period the corresponding reflex forces decreased significantly ($p<0.05$) only in group B. An insignificant decrease in the EMG/force ratio of the reflex contraction was noted during the training of both groups A and B (see also Fig. 6). In all experimental subjects, during training the individual changes in the EMG/force ratio of the reflex contraction correlated significantly

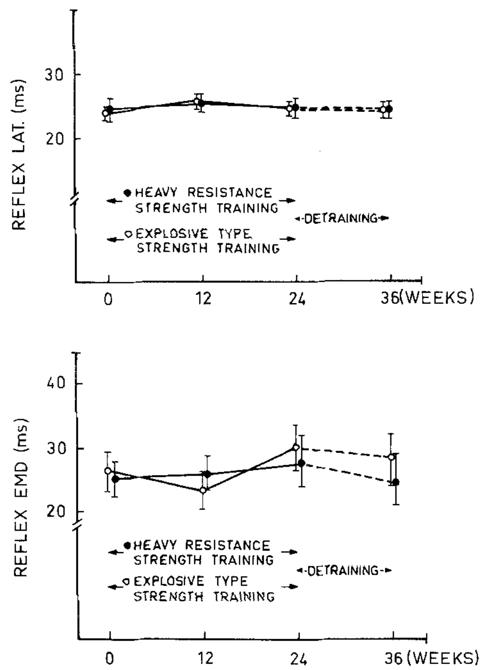

Fig. 4. Mean (±SE) reflex latency (LAT) and reflex electromechanical delay (EMD) (averaged for the three superficial knee extensor muscles) during the heavy resistance and explosive type strength training of the two experimental groups, and after the detraining period

Table 3. The reflex measurements for group A (heavy resistance strength training) and group B (explosive type strength training) before and after 24-weeks training and after the subsequent 12-week detraining, and for the control group

Variable		Before training		After training		After detraining	
		Mean	SD	Mean	SD	Mean	SD
Latency (ms)							
	Group A	24.1	3.8	24.4	3.3	23.7	2.2
	Group B	22.9	1.7	24.5	2.0	23.4	2.8
	Control	25.1	3.1	25.6	3.5	—	
Electromechanical delay (ms)	Group A	25.4	7.2	28.1	9.5	24.4	7.4
	Group B	27.0	8.9	30.5	9.3	27.4	10.8
	Control	21.0	7.0	26.9	9.5	—	
Peak-to-peak EMG amplitude (mV)	Group A	0.55	0.42	0.43*	0.40	0.44	0.50
	Group B	0.52	0.24	0.30*	0.22	0.35	0.17
	Control	0.65	0.51	0.31	0.45	—	
Peak-to-peak force amplitude (N)	Group A	32.0	31.8	27.6	35.3	24.2	32.0
	Group B	23.2	6.4	15.7*	5.8	15.2	3.9
	Control	26.0	10.0	19.8	8.5	—	
EMG/force ratio							
	Group A	0.020	0.010	0.019	0.006	0.020	0.012
	Group B	0.024	0.016	0.019	0.009	0.022	0.006
	Control	0.024	0.013	0.017	0.012	—	

* $= p < 0.05$

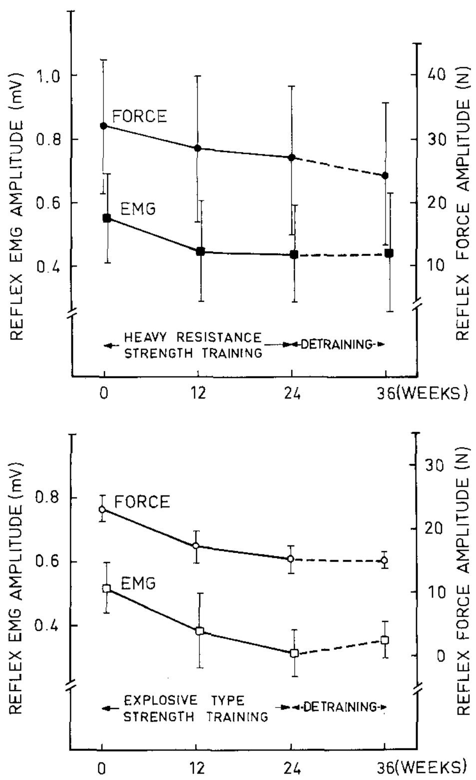

Fig. 5. Mean (±SE) peak-to-peak amplitudes of reflex EMG (averaged for the three superficial knee extensor muscles) and of reflex force of the knee extensors during the heavy resistance and explosive type strength training of the two experimental groups, and after detraining

($r = 0.59$, $p < 0.01$) with the corresponding changes in maximal IEMG/force ratio during the voluntary contraction (Fig. 7). Only minor changes were noted in the amplitudes of EMG and force and their ratio during the detraining period. In the control group no significant changes in the measured reflex parameters were noted.

Discussion

The present heavy resistance and explosive type strength training regimens resulted in specific

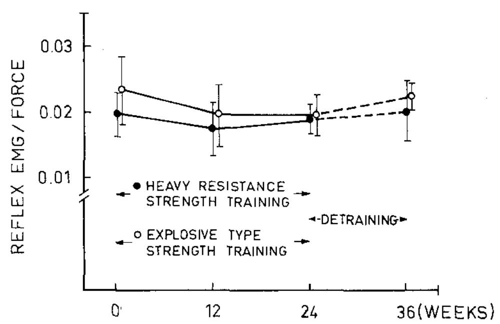

Fig. 6. Mean (±SE) ratios of peak-to-peak amplitudes of reflex EMG (averaged for the three superficial knee extensors) and force of the knee extensors during the heavy resistance and explosive type strength training of the two experimental groups, and after detraining

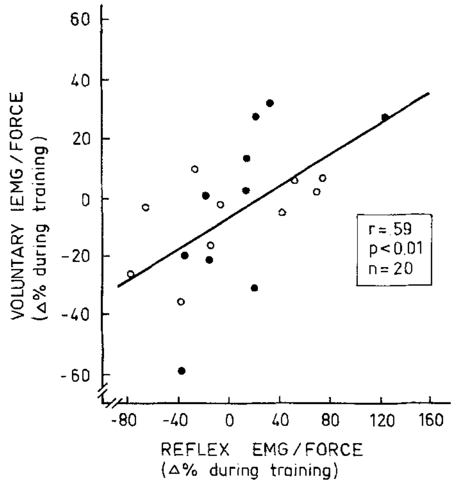

Fig. 7. Relationship between the relative changes of the voluntary IEMG/force ratio of the unilateral knee extension and the respective reflex EMG/force ratio (EMGs averaged for the three superficial knee extensors) after the heavy resistance (●) and explosive type (○) training of the two experimental groups

changes in voluntary neuromuscular performance capacity. This was demonstrated by great improvement in maximal force during heavy resistance strength training, with only minor changes in the time of force production. Greater improvements in force-times on the relative scale were observed during explosive type strength training, with only minor increases in maximal force. The increase in maximal force during high loading training was accompanied by and related to an increase in maximum IEMG of the trained muscles. No changes were noted during training in reflex time components. However, significant decreases in the peak-to-peak amplitudes of the reflex EMG were observed in both groups, while the corresponding force remained unaltered in the heavy resistance group. The individual changes during training in the EMG/force ratio of the reflex contraction were related to the respective changes in maximal IEMG/force ratio of the voluntary contraction. The following discussion will concentrate on these findings and their interpretations.

The present findings concerning changes in the voluntary force-time curve strongly support the concept of specificity of training. Greater increases in maximal strength are expected during heavy load strength training with only minor improvements in the time of force production (e.g., Sukop and Nelson 1974; Häkkinen et al. 1980; 1981; 1985a) or in the velocity portions of the force-velocity curve (e.g., Ikai 1970; Caiozzo et al. 1981; Coyle et al. 1981). On the other hand, the present explosive type strength training utilizing high contraction velocities with low loads resulted in considerable improvements in the time of isometric force production measured on the relative scale, while the increase in maximal force was only slight. This finding is well in line with previous observations, demonstrable both in force-time (e.g., Viitasalo et al. 1981; Komi et al. 1982) and in force-velocity curves (e.g., Ikai 1970; Caiozzo et al. 1981; Coyle et al. 1981).

The improvement in maximal force in the heavy resistance strength training group was accompanied by significant increases in neural activation of the trained muscles. The increased maximal IEMG activity during high loading strength training can therefore be attributed to the present training effect. The significant correlation noted (Fig. 3) between the increases in IEMG and in force further emphasizes the importance of adaptation of neural activation for maximal force development. The notions about the correlative decreases during detraining between maximum IEMG and muscle strength are well in line with this suggestion. This increase in neural activation during high load strength training may suggest that a part of the effect resides in the facilatory and inhibitory neural pathways acting at various levels in the nervous system (Moritani and De Vries 1979; Häkkinen and Komi 1983a). The time course of these training-induced increases in neural activation and consequently in muscle strength may, however, be related to the type and/or intensity of training and especially to the duration of the training period (Häkkinen et al. 1985a). Because the measurements were performed only at twelve week intervals, accurate examination of this phenomenon was not possible in the present experiment (Häkkinen et al. 1985a). Documented data are additionally available (e.g., MacDougall et al. 1977; Häkkinen et al. 1981; Komi et al. 1982) to demonstrate that heavy resistance strength training may result in enlargements in area of both types of muscle fibre, contributing to increases in maximal strength. Greater hypertrophy was noted during the present heavy resistance strength training (Häkkinen et al. 1985a) in comparison with the slighter hypertrophy noted during the explosive type strength training (Häkkinen et al. 1985b). These observations may therefore additionally explain the greater improvement in maximal unilateral knee extension force noted in the present heavy resistance strength training in contrast to that of the explosive type strength training.

The present explosive type strength training resulted in improvements in time of isometric force production, observable especially on the relative scale (see Table 2 and Fig. 2). Plausible explanations for this specific increase might result from both neural and muscular adaptations. Adaptations with respect to firing frequencies (Kawakami 1955; Cracroft and Petajan 1977) and/or the recruitment pattern of the activated motor units during explosive type activation may have taken place during the present training, contributing to the improvement in the time of force production. The correlative, although statistically insignificant, increases noted between the earlier portions of the average IEMG/time curve and the respective portions of the force-time curve tend to support this possibility. Another plausible mechanism for the improvement in explosive force production may have resulted from a training-induced hypertrophy of particularly the fast twitch muscle fibers reported to take place during this type of training (Komi et al. 1982; Häkkinen et al. 1985b).

In reflex induced contractions, no statistically significant changes were observed in reflex time components during the present two training regimens. As regards reflex latency, the present results may therefore indicate that no changes had occurred in the sensory and/or motor nerve conduction characteristics. This observation is in line with our previous notions on heavy resistance strength training (Häkkinen and Komi 1983b). The present findings, that no changes took place in reflex latency during detraining, tend additionally to support the consistency of this phenomenon. The reflex EMD also remained unaltered during the two training and detraining periods (see also Häkkinen and Komi 1983b), although decreases in total reflex time due to strength training have been reported (e.g., Francis and Tipton 1969). The present observations indicate that the peripheral motor time component may not be very sensitive to the kinds of training utilized.

However, the two present training regimens resulted in significant decreases in amplitude of the reflex EMG, while a slight and insignificant decrease in reflex force was noted in the heavy resistance strength training group. The former observation may imply that, for example, a decrease in the sensitivity of muscle spindle response may have occurred during the training, as suggested earlier (Häkkinen and Komi 1983b) for heavy resistance strength training. Slight increases noted in reflex EMG during the following detraining periods in both groups tend additionally to support this possible training-induced decrease in the sensitivity of the muscle spindles. This decrease may result from possible morphological changes in the intrafusal fibers caused by training. The present training may have resulted in changes similar to those reported by Maynard and Tipton (1971), observable as increases in mean cross-sectional area of the nuclear chain fibers with no responses in the nuclear bag fibers. This would result in an enhancement of inhibitory drive from the group II afferents, while the contribution of the facilatory primary (Ia) afferents would remain unaltered. It is also possible (Milner-Brown et al. 1975) that, while direct supraspinal connections from the motor cortex to spinal motoneurons may be enhanced as a result of training, no differences might be obtained in earlier spinal reflexes resulting from the passive stimulation of the "resting" primary muscle spindle sensory fibers. Possible training-induced changes in the roles of gamma discharge (e.g., Maynard and Tipton 1971) and of Golgi tendon organs in their contributions to reflex responsiveness must also be taken into consideration. It is naturally very difficult to determine the exact mechanisms involved, due to the limitations of present methodology. In spite of this decrease in reflex EMG, the mechanical response of the muscle remained, however, concomitantly unaltered in the heavy resistance strength training group. This may result from improvement in the strength of individual motor units during the high loading training. The correlative changes noted in all test subjects (Fig. 7) in the reflex EMG/force ratio and in that of voluntary contraction tend to support this notion.

It can be expected that the training-induced changes in reflex responsiveness measured in relaxed muscles may differ completely from those which occur when the active muscle is subjected to a forceful stretch. We have earlier speculated that improvement in the stiffness regulation of muscle is one of the primary objectives of neuromuscular training (Komi 1986). In this regulation, the length feedback component of the hypothetical stretch reflex (Houk 1974), functioning through the muscle spindles, would contribute to increased stiffness by increasing the spindle discharge for a given stretch load. Correspondingly the force-feedback component operating via the inhibitory connection from the Golgi tendon organ would decrease during strength/power training.

In summary, it can be concluded that the present heavy resistance and explosive type strength training regimens resulted in specific changes in voluntary neuromuscular performance capacity. Great improvement in maximal strength with only minor changes in time of force production were observed during heavy resistance strength training, while explosive type strength training caused only slight increase in muscle strength but considerable shortening in the times of force production. The increase in maximal strength during high loading training was accompanied by and correlated with significant increase in the neural activation of the trained muscles. No changes were noted during training in reflex time components. However, significant decreases were observed in reflex EMG, while the corresponding reflex force remained unaltered during high load strength training. These decreases in EMG indicate, for example, a change in the sensitivity of the muscle spindles. The individual changes during training in the EMG/force ratio of reflex contraction were related to the respective changes in the IEMG/force ratio of voluntary contractions, indicating individual training-induced changes in the mechanical response of individual muscle fibers of the respective motor units. The present observations support the concept of specificity of training, and suggest that specific training-induced adaptations in the neuromuscular system may be responsible for these changes in performance.

Acknowledgement. This study was supported in part by a grant from the Ministry of Education, Finland.

References

Caiozzo V, Perinne J, Edgerton V (1981) Training-induced alternations of the in vivo force-velocity relationship of human muscle. J Appl Physiol: Respirat Environ Exercise Physiol 51:750–754

Coyle E, Feiring C, Rotkis T, Cote R, Roby F, Lee W, Wilmore J (1981) Specificity of power improvements through slow and fast isokinetic training. J Appl Physiol: Respirat Environ Exercise Physiol 51:1437–1442

Cracroft JD, Petajan JH (1977) Effect of muscle training on the pattern of firing of single motor units. Am J Phys Med 56:183–194

Francis P, Tipton C (1969) Influence of a weight training program on quadriceps reflex time. Med Sci Sports 1:91–94

Häkkinen K, Komi PV (1983a) Electromyographic changes during strength training and detraining. Med Sci Sports Exerc 15:455–460

Häkkinen K, Komi PV (1983b) Changes in neuromuscular performance in voluntary and reflex contraction during strength training in man. Int J Sports Med 4:282–288

Häkkinen K, Viitasalo JT, Komi PV (1980) Die Wirkung unterschiedlich kombinierter konzentrischer und exzentrischer Muskelarbeit auf Kraft-Zeit-Merkmale der Beinstreckmuskulatur. Leistungssport 10:374–381

Häkkinen K, Komi PV, Tesch P (1981) Effect of combined concentric and eccentric strength training and detraining on force-time, muscle fibre, and metabolic characteristics of leg extensor muscles. Scand J Sports Sci 3:50–58

Häkkinen K, Alén M, Komi PV (1985a) Changes in isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of human skeletal muscle during strength training and detraining. Acta Physiol Scand 125:573–585

Häkkinen K, Komi PV, Alén M (1985b) Effect of explosive type strength training on isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of leg extensor muscles. Acta Physiol Scand 125:587–600

Häkkinen K, Pakarinen A, Alén M, Komi PV (1985c) Serum hormones during prolonged training of neuromuscular performance. Eur J Appl Physiol 53:287–293

Houk HC (1974) Feedback control of muscle: a synthesis of the peripheral mechanisms. In: Mountcastle WB (ed) Medical physiology (13th ed). Mosby, St. Louis Mo, pp 668–677

Ikai M (1970) Training of muscle strength and power in athletes. Presented at the FIMS Congress, Oxford

Kawakami M (1955) Training effect and electro-myogram. I spatial distribution of spike potentials. Jpn J Physiol 5:1–8

Komi PV (1986) Training of muscle strength and power: Interaction of neuromotoric, hypertrophic and mechanical factors. Int J Sport Med (in press)

Komi PV, Viitasalo J, Rauramaa R, Vihko V (1978) Effect of isometric strength training on mechanical, electrical and metabolic aspects of muscle function. Eur J Appl Physiol 40:45–55

Komi PV, Aho V-J, Tervakari M (1979) Measurement of potentiation of muscular performance after prestretching. Presented at American College of Sports Medicine Congress, Honolulu, May 24–26

Komi PV, Karlsson J, Tesch P, Suominen H, Heikkinen E (1982) Effects of heavy resistance and explosive type strength training methods on mechanical, functional and metabolic aspects of performance. In: Komi PV (ed) Exercise and sport biology. Human Kinetics Publishers, Champaign, Ill, pp 90–102

MacDougall J, Elder G, Sale D, Moroz J, Sutton J (1977) Skeletal muscle hypertrophy and atrophy with respect to fibre type in humans. Can J Appl Sport Sci (Abstr) 2:229

Maynard J, Tipton C (1971) The effect of exercise training and denervation on the morphology of intrafusal muscle fibers. Int Z Angew Physiol 30:1–9

Milner-Brown H, Stein R, Lee G (1975) Synchronization of human motor units: possible roles of exercise and supraspinal reflexes. Electroenceph Clin Neurophysiol 38:245–254

Moritani T, DeVries H (1979) Neural factors versus hypertrophy in the course of muscle strength gain. Am J Phys Med 58:115–130

Sale D, MacDougall J, Upton A, MacComas A (1979) Effect of strength training upon motoneuron excitability in man. Abstract. Med Sci Sports 11:77

Sale D, MacComas A, MacDougall J, Upton A (1982) Neuromuscular adaptation in human thenar muscles following strength training and immobilization. J Appl Physiol 53:419–424

Sukop J, Nelson R (1974) Effect of isometric training on the force-time characteristics of muscle contraction. In: Biomechanics IV. University Park Press, Baltimore, pp 440–447

Viitasalo J, Saukkonen S, Komi PV (1980) Reproducibility of measurements of selected neuromuscular performance variables in man. Electromyogr Clin Neurophysiol 20:487–501

Viitasalo JT, Aura O, Häkkinen K, Komi PV, Nikula J (1981) Untersuchung von Trainingswirkungen auf die Krafterzeugung und Sprunghöhe. Leistungssport 11:278–281

Accepted January 2, 1986