Eur J Appl Physiol (1999) 80: 485–493

ORIGINAL ARTICLE

Esteban M. Gorostiaga · Mikel Izquierdo
Pilar Iturralde · Maite Ruesta · Javier Ibáñez

Effects of heavy resistance training on maximal and explosive force production, endurance and serum hormones in adolescent handball players

Accepted: 22 April 1999

Abstract To determine the effects of 6-weeks of heavy-resistance training on physical fitness and serum hormone status in adolescents (range 14–16 years old) 19 male handball players were divided into two different groups: a handball training group (NST, $n = 10$), and a handball and heavy-resistance strength training group (ST, $n = 9$). A third group of 4 handball goalkeepers of similar age served as a control group (C, $n = 4$). After the 6-week training period, the ST group showed an improvement in maximal dynamic strength of the leg extensors (12.2%; $P < 0.01$) and the upper extremity muscles (23%; $P < 0.01$), while no changes were observed in the NST and C groups. Similar differences were observed in the maximal isometric unilateral leg extension forces. The height of the vertical jump increased in the NST group from 29.5 (SD 4) cm to 31.4 (SD 5) cm ($P < 0.05$) while no changes were observed in the ST and C groups. A significant increase was observed in the ST group in the velocity of the throwing test [from 71.7 (SD 7) km · h^{-1} to 74.0 (SD 7) km · h^{-1}; $P < 0.001$] during the 6-week period while no changes were observed in the NST and C groups. During a submaximal endurance test running at 11 km · h^{-1}, a significant decrease in blood lactate concentration occurred in the NST group [from 3.3 (SD 0.9) mmol · l^{-1} to 2.4 (SD 0.8) mmol · l^{-1}; $P < 0.01$] during the experiment, while no change was observed in the ST or C groups. Finally, a significant increase ($P < 0.01$) was noted in the testosterone:cortisol ratio in the C group, while the increase in the NST group approached statistical significance ($P < 0.08$) and no changes in this ratio occurred in the ST group. The present findings suggested that the addition of 6-weeks of heavy resistance training to the handball training resulted in gains in maximal strength and throwing velocity but it compromised gains in leg explosive force production and endurance running. The tendency for a compromised testosterone:cortisol ratio observed in the ST group could have been associated with a state of overreaching or overtraining.

Key words Adolescents · Strength training · Handball · Testosterone · Cortisol

E.M. Gorostiaga (✉) · M. Izquierdo · P. Iturralde
M. Ruesta · J. Ibáñez
Centro de Investigación y Medicina del Deporte,
Instituto Navarro de Deporte y Juventud,
Gobierno de Navarra, Paulino Caballero 13,
E-31002 Pamplona, Spain

Introduction

For decades strength training in children and adolescents has been a controversial subject of great concern to the medical and scientific community (Mero et al. 1989; Williams 1993). Historically, resistance training for the development of strength has not been recommended because it has generally been believed that low or insufficient quantities of circulating androgen hormones precluded strength improvement (Kraemer and Fleck 1993; Mero et al. 1989; Zakas et al. 1994). Also, it has been suggested that in adolescents, there are potential risks that include apparent injuries as well as deleterious effects on the musculoskeletal, cardiovascular or other systems (Kraemer and Fleck 1993; Malina and Bouchard 1991; Mero et al. 1989). However, recently, several professional scientific organizations have advocated strength training for young people because recent studies have found that, following certain guidelines, children and adolescents can successfully and safely experience increases in muscle strength (Kraemer and Fleck 1993; Ozmun et al. 1994), and because it has been assumed that regular participation in physical activity that includes strength training is important in potentiating growth and maturation (Malina and Bouchard 1991).

In recent years, pubescent athletes have been training harder, having increased dramatically their training loads (Malina and Bouchard 1991) and introduced heavy resistance training (i.e. intensity >80% of one repetition maximum, 1RM) as normal training for competition sport. This has caused increasing concern about the effects of the addition of this type of strength training on neuromuscular performance and the serum hormones known to regulate pubertal changes, and the stress response to exercise training. In view of the above considerations the purpose of this study was to examine the effects on maximal strength, explosive performance and serum hormones of the addition of heavy-resistance training to the training programme of male adolescent handball players who were participating in five to six handball training sessions per week, handball competitions, and physical education classes. A second purpose of this study was to examine the effects of adding 6 weeks of heavy-resistance strength training on submaximal endurance in adolescent players who play and train for the sport of handball, an activity which predominantly relies on the aerobic energy pathways.

Methods

Subjects

A group of 24 male subjects (mean age 15 years; range 14–16), volunteered for the study with the informed consent of their parents. All were regional handball players from two teams belonging to the same club. They were all trained by the same coach. Their mean experience in handball was [3.5 (SD 1.3) years]. Of the 24 subjects 19 were divided into two matched groups: a handball training group (NST, $n = 10$), and a handball and heavy-resistance strength training group (ST, $n = 9$). Prior to the commencement of training, the two training groups were similar in anthropometric and physiological (neuromuscular, endurance and hormone) measurements. It was difficult to find subjects who were willing to be included in the control group. Therefore, the remaining 5 subjects, who were the team goalkeepers, served as a control group (C). Over the experiment, 2 individuals withdrew from the study through illness. The final breakdown of the three groups was as follows: 9 subjects in the NST group, 9 subjects in the ST group and 4 subjects in the C group. The physical characteristics of the three groups are given in Table 1.

Each subject received a pre-participation medical examination for the purposes of screening for any orthopaedic conditions that would restrict the subject from participating in a weight training programme. The study was conducted according to the declaration of Helsinki and was approved by the Ethics Committee responsible.

Experiment design

This study was performed during the competitive season (from October to May) in a 6-week period from January to March. During this period, all the subjects trained two to three times a week for handball, they played one official handball game each week and took part in a normal school physical education programme twice a week. Practice handball sessions lasted 90 min and usually consisted of various skill activities at different intensities, offensive and defensive strategy, and 30 min of continuous play with only brief interruptions by the coach. The C group maintained this normal frequency of handball training and trained and competed as goalkeepers. School physical education sessions lasted 40-min and consisted mainly of ball games and some calisthenics. In addition to this training, the ST group took part in a heavy-resistance training programme. The subjects were tested before and after the 6-week experiment using identical protocols. Tests were carried out after 1 day of minimal physical activity, on 2 consecutive days, in a fixed order within a period of 1 week. In addition, the ST group was tested between 5 and 9 days after their last strength training session to allow adequate recovery from the heavy resistance training.

Training

The strength training programme consisted of two training sessions each week over a 6-week period. The strength training sessions were performed on Tuesdays and Thursdays, immediately before the handball training sessions. The programme required each subject to perform in each session, heavy-resistance weight lifting exercises consisting of four sets of a five-exercise circuit on a variable resistance gym apparatus (Salter Ltd, Barcelona, Spain). The exercises completed in each weight-training session were the supine bench press, half squat, knee flexion curl, leg press and pec-dec. The first two sets were done with 40% (12 repetitions) and

Table 1 Physical characteristics of the subjects before and after 6 weeks of the experiment. *PH* Pubic hair stage of maturation

	Strength training group				Non strength training group				Control group			
	Before training		After training		Before training		After training		Before training		After training	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Age (years)	15.1	0.7	15.2**	0.7	15.1	0.5	15.2**	0.5	14.8	0.4	15.0**	0.3
Body mass weight (kg)	62.4	7.1	62.7	6.7	67.7	5.5	67.6	5.5	64.8	13.7	65.6	14.2
Height (cm)	173.1	5.3	173.8*	5.5	177.1	6.2	177.7*	6.0	170.6	3.9	171.6	4.8
Fat (%)	11.3	3.1	11.2	3.3	13.2	5.4	12.3	4.7	12.9	4.9	12.9	5.5
Contracted arm girth (cm)	28.7	2.2	29.2**	2.0	29.7	1.3	29.9	1.4	27.4	2.6	27.7	2.6
Arm girth (cm)	25.2	2.1	25.4	2.1	26.4	0.9	26.7	1.0	25.1	2.6	25.2	2.9
Forearm girth (cm)	26.0	1.4	26.2	1.3	26.7	0.9	26.7	0.9	25.9	2.1	26.1*	2.1
Thigh girth (cm)	52.9	3.5	53.0	2.9	56.1	3.6	55.8	3.4	58.3	6.3	55.9	7.0
Calf girth (cm)	35.4	2.1	35.6	1.9	36.4	2.1	36.5	2.0	36.1	4.3	36.5**	4.4
PH (Tanner)[a]	5.2	0.5	5.2	0.5	5.5	0.5	5.5	0.5	4.7	0.5	4.9	0.2
Range	4.5–6.0		4.5–6.0		4.5–6.0		4.0–6.0		4.0–5.5		4.5–5.0	

$*P < 0.05$, $**P < 0.01$ Statistical significances of the examined parameters before and after the training period. [a] Tanner (Ross and Marfell-Jones 1991)

50% (10 repetitions) of the individual's 1RM, respectively. The third and fourth sets were done at 80% and 90% of the individual's 1RM, with six and three repetitions respectively. Approximately 1.5-min rests were given between each set and each exercise. The total duration of each strength training session was 40 min.

In total, the handball training and competition, combined with the school physical education courses, provided each subject in the NST and C groups with five to six sessions a week. In addition to this training, the ST group strength-trained twice a week, therefore the total number of training sessions in this ST group was seven to eight a week. Because the handball players belonged to the same club and were trained by the same coach, their training schedules were fairly well synchronised. The coach kept training diaries during the whole experiment so that training could be analysed in detail.

Tests

The subjects were carefully familiarised with the test protocol and circuit training/lifting techniques 2 weeks before the measurements and training period. Also the subjects were familiarised with the 1RM test procedure and a theoretical maximal load was calculated. During the actual test, several warm-up exercises were performed prior to the maximal tests.

Neuromuscular performance characteristics of the right-knee extensor muscles were measured using a David Rehab 2200 lower limb testing unit (David Rehab Systems Ltd., Vantaa, Finland; Häkkinen et al. 1987). On command, the subjects made three maximal isometric knee extensions and flexions seated in an adjustable chair with the seat angle at 100° and the knee flexed at 60° (for extension and flexion; Häkkinen et al. 1987). A rest of 1 min between successive trials was allowed. Each subject was instructed to exert his maximal force as fast as possible during 2–4 s. A computerised off-line analysis was performed for detailed investigation of the force-time curve. In this analysis the calculations were concerned primarily with the maximal isometric strength and the time taken from the beginning of force production to the attainment of 25%, 50% and 75% of the maximal voluntary isometric contraction. In addition, the maximal rate of force development (RFD) was calculated as the greatest increase in force for a given 10-ms period (Viitasalo et al. 1980).

Maximal dynamic strength of the leg extensor and upper extremity muscles was measured in a variable resistance machine (Salter Ltd., Barcelona, Spain) as the maximal mass that could be lifted for 1RM. The exercises chosen for 1-RM tests were the leg-press (leg extensor muscles) and the pec-dec (upper extremity muscles). The 1-RM tests consisted of multiple trials. The initial mass represented around 50% of the theoretical maximum reached during the familiarisation day of testing. Later, the masses were increased and the last mass successfully lifted through the full range of motion was considered the 1-RM (Mero et al. 1989). A rest of 2–3 min between successive trials was taken. In addition to the 1-RM tests performed before and after the 6-week experiment, the 1-RM test was performed after 2 weeks of training in the ST group to maintain a similar relative resistance throughout training.

The characteristics of the dynamic explosive force of the leg muscles were measured on a contact platform (Digitest OY, Finland) using a maximal vertical squat jump (SJ; from a semi-squatting position with a knee angle of 90°), and a counter movement jump with a preparatory movement from the extended leg position down to 90° of the knee flexion, followed by a subsequent concentric action; Häkkinen and Komi 1983; Häkkinen 1993; Komi and Bosco 1978). A digital timer was connected to the contact platform to measure the flight times of the jumps. The flight time measured was used to calculate the height of rise of the centre of gravity of the body. The movement amplitude of the knee joint during each jump was measured with a flexible electrogoniometer (Penny and Giles Co., England) attached to the lateral side of the subject's left knee joint. Three to five maximal jumps were recorded in both cases and the best reading was used for further analysis.

The explosive strength production of the upper trunk and upper extremity muscles was evaluated by a throwing test as has been used by Viitasalo (1988). After warming up, the subjects threw an official handball ball at maximal speed through a photocell gate (Digitest OY, Finland) to a contact mat hanging on a wall. The throws were performed with one hand from a standing position, each subject using his own technique for throwing a handball penalty. When the ball passed through the photocell gate, it started a digital timer. The timer stopped when the ball hit the contact mat giving the flight time. With a fixed distance between the photocell gate and contact mat, the average velocity of the ball could then be calculated. The coach supervised all the throwing tests to ensure that the subjects were using the right handball technique. Each subject performed two series of three throws. A 1–2 min rest was taken between each of the series of throws and 10–15 s elapsed between two throws of the same series.

Endurance capacity was assessed by a running test. Each subject ran submaximally on a motorised treadmill (Jaeger, Mod. Laufergotest, Germany) for two 10-min periods with a 2-min rest between each run. The treadmill velocity for the first run was $10\ km \cdot h^{-1}$ and for the second run it was $11\ km \cdot h^{-1}$. The treadmill inclination was (+1%). Heart rate was monitored each 15 s using a cardiotachometer (Sportester Polar, Finland). Arterialised blood samples were taken from the hyperaemic earlobe using capillary tubes, to determine total blood lactate concentration (YSI, 1500 Sport L-Lactate Analyzer, USA). The samples were taken when the subjects were at rest and at the end of each 10-min run (allowing 30 s for recovery). Our criterion of endurance capacity was the blood lactate concentration elicited during submaximal exercise at a given velocity because it has been shown to be more consistent than the inconsistent relationship observed between maximal oxygen uptake ($\dot{V}O_{2\,max}$) and endurance performance capacity (Lafontaine et al. 1981; Marcinik et al. 1991).

Some subjects were selected at random to estimate daily physical activity by wearing heart rate monitors during, on average, 6 h a day. Heart rate was recorded in memory every 15 s to assess the physical activity during some handball training sessions and games, physical education courses and leisure times. The subjects were assessed on different days when three daily activities were performed: (1) a day with a physical education course (PE), (2) a day with a handball training session (H), and (3) a day with no scheduled physical activity (N). The total number of minutes spent at heart rate above 140 beats $\cdot$ min^{-1} was computed. This value has been used as an activity index above the anaerobic training threshold (Janz et al. 1992).

The pubertal stage was evaluated using secondary sex characteristics, the pubic hair, following the criteria described by Tanner (Ross and Marfell-Jones 1991), and from the basal blood testosterone concentrations, with all testosterone concentrations falling within the range that has been recorded for each subject's age (Malina and Bouchard 1991).

Analytical methods

After 12 h of fasting and 1 day of minimal physical activity, venous blood samples were obtained at rest at 8 a. m. from an antecubital vein to determine concentrations of serum total testosterone and cortisol. Serum samples for the analyses of hormones were kept frozen at −20°C until analysed. The assays of serum cortisol and testosterone were performed by radioimmunoassays. Serum testosterone and cortisol concentrations were measured using reagent kits from Diagnostic Product Corporation and INCSTAR corporation (Coat-A-Count Total testosterone TKTT1CS, Los Angeles, USA and GammaCoat Cortisol Radioimmunoassay Kit, USA). The sensitivities of the testosterone and cortisol assays were $0.14\ nmol \cdot l^{-1}$ and $0.21\ \mu g \cdot dl^{-1}$, respectively. The coefficient of intraassay variation was 5% and that of interassay variation was 5.9%. The values were 6.6% and 8.8%, respectively, for the cortisol assay. All samples for each subject were analysed in the same assay for each hormone according to the instructions of the manufacturer.

Anthropometric measurements

Percentage of body fat was calculated from measurements of skinfold thickness (Drinkwater and Ross 1980). Thigh, forearm and arm circumference were determined using a tape applied around the relaxed and the contracted muscles with the subject in a sitting position. The medial portion of the thigh was measured. The arm, forearm, and calf girths were measured at their greatest girth while contracting the muscles maximally (Häkkinen 1989).

Statistical procedures

The effects of training in each group were tested with one-way analyses of variance (ANOVA), using the Scheffé test to establish differences between groups. The probability level accepted for statistical significance was $P < 0.05$.

Results

Daily physical activity

The mean heart rates recorded during the daily monitoring of heart rate were no different between the ST group [88.7 (SD 12.0)] and the NST group [88.9 (SD 12.6)]. Mean time spent daily above a heart rate of 140 beats · min^{-1} was 23.3 (SD 29) min in the ST group and 19.4 (SD 28.5) min in the NST group. There were no differences between the groups.

Because no differences were observed between groups in the estimation of daily physical activity, all the observations were analysed together to evaluate the pattern of time spent at heart rates above 140 beats · min^{-1} in days when the N, PE and H activities were performed. The mean number of minutes spent daily at heart rates above 140 beats · min^{-1} was higher in H days [62.8 (SD 31) min] than in N [5.5 (SD 13) min] or PE days [14.2 (SD 19) min] ($P < 0.001$). There was no differences in the mean number of minutes spent at heart rates above 140 beats · min^{-1} between the N and PE days.

Handball and strength-training sessions

During the 6-week training period, the mean number of handball training sessions performed in the ST group was 15.5 (SD 2.5) (range 11–18) and 15.3 (SD 2.2) in the NST group (range 11–17). During this period, the average number of strength training sessions performed in the ST group was 11.0 (SD 0.7) (range 10–12).

Anthropometric measurements

Only a few slight changes occurred in physical characteristics of the subjects during the 6-week experiment (Table 1). The ST group gained significantly in height ($P < 0.01$), and contracted arm girth ($P < 0.01$). The NST group gained significantly in height ($P < 0.01$), while the mean values for the remaining measured physical characteristics were unaltered in this group. The C group gained significantly in forearm girth ($P < 0.05$) and calf girth ($P < 0.01$).

Maximal forces and force-time

During the 6-week training period, the mean 1-RM performance in the ST group improved in the leg extensor muscles (leg press) from 126.7 (SD 21) kg to 142.2 (SD 18) kg ($P < 0.01$), and in the upper extremity muscles (pec dec) from 36.1 (SD 9) kg to 44.4 (SD 9) kg ($P < 0.01$) (Fig. 1). The NST and C groups showed no changes in 1-RM performance between tests. The increase in maximal dynamic force occurred mainly during the first 2 weeks, whereas there was only a slight improvement (not significant) during the following 4-weeks of training (Fig. 2).

The mean maximal isometric unilateral leg extension force increased in the ST group during the 6-week strength training period from 208 (SD 29) N · m to 235.8 (SD 41) N · m ($P < 0.01$; Table 2). The maximal unilateral leg flexion force increased in the ST group from 100 (SD 12) N · m to 109 (SD 15) N · m ($P < 0.05$). The NST and C groups showed no significant changes for the maximal isometric leg extension and flexion forces between the pre-and post-test periods.

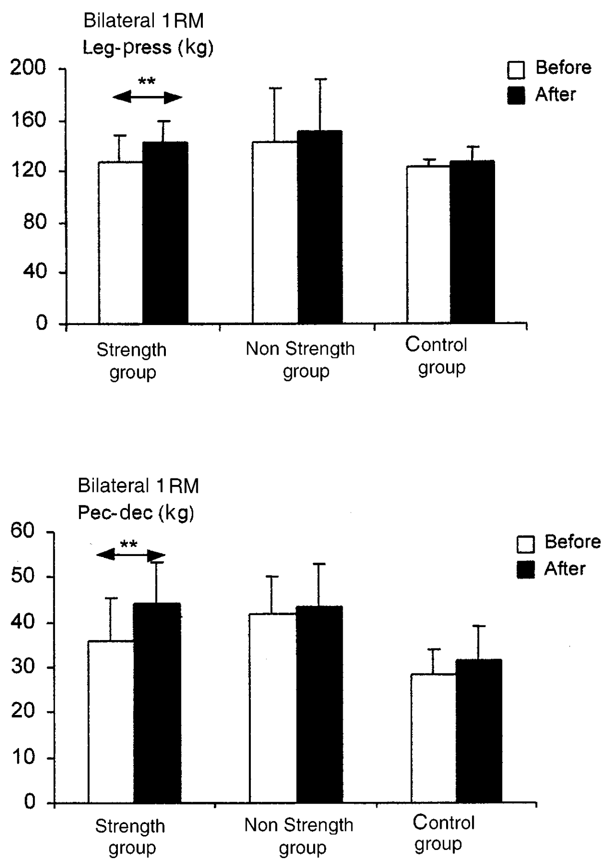

Fig. 1 Maximal strength (one repetition maximum, *1RM*) under dynamic conditions of the upper and lower limb muscles before and after the 6-week experiment (**$P < 0.01$)

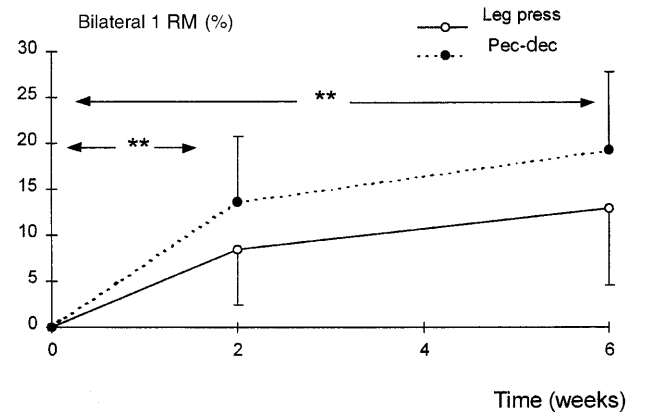

Fig. 2 Relative alterations in the leg press and the pec dec in the heavy resistance strength training group during the course of the 6-week strength training (**$P < 0.01$). *1RM* One repetition maximum

On the relative scale, the time to produce certain forces (50% and 75% of maximal isometric leg extensor forces) was significantly lengthened in the ST group after 6 weeks of training, while no significant changes were observed in the NST group and control group during this period (Table 2).

Explosive forces

Only some slight changes occurred in jumping performance during the 6-week experiment. Mean jump height in SJ increased in the NST group from 29.5 (SD 4) cm to 31.4 (SD 5) cm ($P < 0.01$; Table 3). In the ST and C groups there were no changes in the performance of the jumping tests during the experiment. A significant increase ($P < 0.001$) was observed in the ST group in the velocities of the throwing test [from 71.7 (SD 7) to 74 (SD 7) $km \cdot h^{-1}$] during the 6-week period, while no changes were observed in the throwing tests in the NST or C groups (Table 3).

Running test

A significant decrease in mean blood lactate concentration was observed in the NST group at treadmill velocities of 10 $km \cdot h^{-1}$ [from 2.6 (SD 1.4) to 1.9 (SD 1) $mmol \cdot l^{-1}$] ($P < 0.01$) and 11 $km \cdot h^{-1}$ [from 3.3 (SD 0.9) to 2.4 (SD 0.7) $mmol \cdot l^{-1}$] ($P < 0.01$) during the experiment. No significant change was observed in mean blood lactate concentration in the ST group at 10 $km \cdot h^{-1}$ [from 2.5 (SD 1.1) to 1.9 (SD

Table 2 Maximal unilateral isometric strength and force-time characteristics of the knee extension and flexion muscles before and after the 6-week experiment. *RFD* Rate of force development

	Strength training group				Non strength training group				Control group			
	Before training		After training		Before training		After training		Before training		After training	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Knee extension												
Maximum strength ($N \cdot m$)	208	29.1	235.8**	41.1	225.8	39.6	239.2	46.9	192.5	8.3	211	12.2
Time 25% of force (ms)	81	10	88	16	93	8	101	23	90	16	85	5
Time 50% of force (ms)	118	19	147*	28	136	16	174	63	147	36	147	34
Time 75% of force (ms)	208	47	351*	172	228	35	392	299	245	58	342	215
RFD ($N \cdot m \cdot s^{-1}$)	1121	195	1061	172	1114	228	998	249	897	224	992	160
Knee flexion												
Maximal strength	100	12.2	109*	15.4	111	25.4	113	30.9	93.7	15.6	97.7	12.2
Time 25% of force (ms)	87	26	86	13	107	19	95	14	142	98	102	25
Time 50% of force (ms)	132	41	137	21	161	23	144*	15	190	100	182	99
Time 75% of force (ms)	434	499	245	69	245	41	230	28	272	105	427	372

*$P < 0.05$, **$P < 0.01$

Table 3 Values of height of centre of gravity in squatting and counter movement jumps in the experimental groups before and after the 6 week-experiment. The average velocity values of upper extremity throwing are also shown

	Strength group				Non strength group				Control group			
	Before training		After training		Before training		After training		Before training		After training	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Squat jump (cm)	32.2	3.2	33.3	3.3	29.5	4.2	31.4**	4.9	27	4.0	28	3.2
Countermovement jump (cm)	34.1	3.1	35.2	3.6	32.0	5.0	32.8	4.9	32	25.5	32.8	24
Throwing velocity ($km \cdot h^{-1}$)	71.7	6.7	74***	7	76.3	3.8	74.7	3.9	64.6	2.5	63.2	1.7

**$P < 0.01$, ***$P < 0.001$

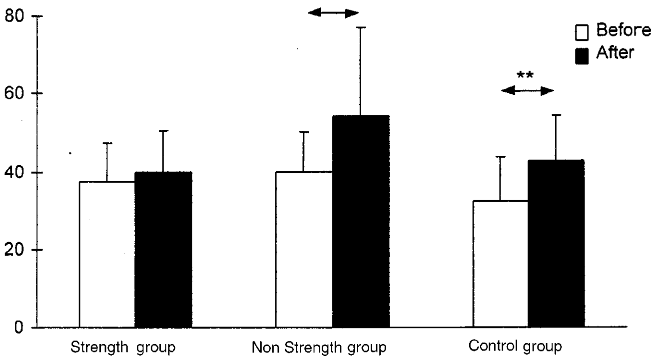

Fig. 3 Serum testosterone:cortisol concentration ratios in the experimental groups before and after the 6-week experiment (*$P < 0.08$, **$P < 0.01$)

1.0) mmol · l^{-1}] and 11 km · h^{-1} [from 4.0 (SD 1.8) mmol · l^{-1} to 3.3 (SD 1.4) mmol · l^{-1}]. Similarly, no significant change was observed in C group at 10 km · h^{-1} [from means 2.9 (SD 2.7) mmol · l^{-1} to 2.6 (SD 2.0) mmol · l^{-1}] and 11 km · h^{-1} [from means 3.2 (SD 1.5) mmol · l^{-1} to 3.1 (SD 1.9) mmol · l^{-1}].

Serum hormone concentrations

Mean blood testosterone concentrations were not significantly altered during the period of training in the ST group [from 21.8 (SD 8) to 21.5 (SD 5) nmol · l^{-1}], the NST group [from 21.3 (SD 3) to 21.6 (SD 4) nmol · l^{-1}] and the C group [from 19 (SD 8) to 21.3 (SD 7) nmol · l^{-1}]. Similarly, the mean serum cortisol did not change significantly in any group. The mean values for pre and post serum cortisol were 0.57 (SD 0.10) to 0.55 (SD 0.10) μm mol · l^{-1} in the ST group, 0.55 (SD 0.13) to 0.45 (SD 0.16) μm mol · l^{-1} in the NST group, and 0.57 (SD 0.11) to 0.50 (SD 0.06) μm mol · l^{-1} in the C group. Figure 3 shows the alteration of mean serum testosterone:cortisol ratio in all the groups before and after the 6-week experiment. A significant increase ($P < 0.01$) was noted in this ratio during the experiment in the C group while the increase approached statistical significance ($P < 0.08$) in the NST group. No change occurred in the testosterone:cortisol ratio in the ST group.

Discussion

The results of this study showed that training adolescents for handball resulted in improvements in explosive force of the leg and endurance running. The addition of heavy resistance training to the handball training resulted in gains in maximal strength and throwing velocity, but it may have compromised gains in the production of explosive force in the leg and endurance running.

The addition of a 6-week period of heavy strength training resulted in considerable gains in the maximal muscle force of the leg extensor muscles (13%) and the arm muscles (23%) with minor changes in the maximal isometric force of the leg flexor muscles (9%). The increase in maximal strength observed in the legs was similar in training-mode specific (1-RM lifts) and non specific (isometric) tests. The magnitude of maximal force gains observed in this study agreed with the findings of previous research in children (Ozmun et al 1994; Ramsay et al. 1990) and adults (Häkkinen et al. 1981; Hennessy and Watson 1994; Hickson 1980; Hoff and Almasbakk 1995) and indicated that the pubertal boys made similar relative strength gains compared to these populations.

Some differences were observed for the strength gains between the upper extremity muscles and the leg extensor muscles as a result of the addition of heavy resistance training. Thus, greater relative strength gains occurred in the ST group in maximal dynamic force in the upper extremity muscles (23%) than in the leg extensor muscles (12%). In addition, the explosive force of the upper body muscles increased (3%) during the experimental period in the ST group while no changes occurred in the performance of the jumping test in this group (Table. 3). A difference in strength gains between upper and lower extremity muscles has been recently found in other studies in adolescents and has been explained by a difference in initial conditioning between knee extensor and upper body muscles (Malina and Bouchard 1991; Ramsay et al. 1990) related to differences in the pattern of quantity and/or intensity of daily physical use in normal life (Enoka 1988; Häkkinen 1994; Winegard et al. 1996). The quadriceps muscle, owing to its weight bearing role during habitual activity, would be more likely to be at a higher initial level of conditioning than the upper body muscles, which have been shown to be used habitually less frequently (Ramsay et al. 1990).

An alternative explanation could be related to some interference of handball training with heavy resistance training in the legs. Some studies investigating the effects of concurrent strength and endurance training have found an interference with optimal development of muscle strength (Dudley and Djamil 1985). Handball training sessions and competitive games place energy production demands on the leg muscles mainly through aerobic processes. This was supported by the finding that more than 60 min per handball session were spent, on average, at heart rates above 140 beats · min^{-1}. Therefore, the aerobic nature of the handball training games and drills might impede optimal gains in maximal and explosive strength in the legs.

Minor changes were observed in limb circumferences and skinfold measurements in the ST group during the training period. This would imply that muscle hypertrophy did not accompany the strength gains and that the increase in strength with training was largely due to specific neurological adaptations as has been suggested by Ozmun et al. (1994) and Ramsay et al. (1990). These results are consistent with most studies performed in adults, which have found that when high training loads are used in previously untrained subjects, early increases in strength may be accounted for to a large extent by neural adaptation (Häkkinen et al. 1985).

No improvement in explosive dynamic force production of the leg extensor muscles was observed in the ST group after the 6-week training period. In fact, heavy strength training seemed to interfere with optimal development of explosive strength in the legs, because the time taken to reach certain force levels on the relative scale (50%, 75%) were increased. Furthermore, the vertical jumping power was compromised in the ST group because it did not change during the 6-week period while in the NST group there was a significant improvement in vertical SJ. These results demonstrate the specificity of the present strength training regime and support the results of other studies which have shown that when high training loads with slow contraction velocities are used, there is significant improvement in maximal muscle strength while little improvement, or even some negative changes are observed in muscle power development (Häkkinen et al. 1985; Häkkinen 1988).

Lowered blood lactate concentrations during submaximal treadmill running were observed in the NST group during the experiment while no change was observed in blood lactate concentrations in the ST group. It has been suggested that a decrease in blood lactate concentrations during submaximal continuous exercise as a result of training is associated with improved endurance performance (Weltman 1995). These results would suggest that the handball training, games and drills resulted in an improvement in submaximal endurance in the NST group and support the concept that handball makes demands predominantly of an aerobic nature. The absence of changes in submaximal blood lactate concentrations observed in the ST group would suggest that in this group concurrent strength and handball training interfered with the optimal development of endurance running.

The influence of strength training on endurance performance is an unresolved question. Earlier studies have found that concurrent strength and endurance training interfered with optimal development of muscle strength but, in contrast, did not affect the development of endurance (Dudley and Djamil 1985; Hickson 1980). However, recent studies have found that the addition of strength training has a negative influence on endurance (Andersen et al. 1992; Rusko and Bosco 1987). Differences in training programmes, experimental design and particularly in the way of estimating endurance could explain the controversy. Indeed, when $\dot{V}O_{2\,max}$ was the criterion for endurance, strength training had no effect on performance (Dudley and Djamil 1985; Hickson 1980; Paavolainen et al. 1991).

However, when blood lactate concentration response to submaximal exercise or some markers of muscle respiratory capacity (i.e. citrate synthase activity) were the criteria of endurance, strength training interfered with optimal development of endurance performance (Andersen et al. 1992; Rusko and Bosco 1987). It has been suggested that the blood lactate concentration response to exercise and $\dot{V}O_{2\,max}$ are determined by different factors, with $\dot{V}O_{2\,max}$ being dependent on cardiovascular factors, such as cardiac output and stroke volume, and the blood lactate concentration response to exercise being dependent on peripheral factors, such as muscle fibre type or the number of mitochondria (Aunola et al. 1988; Weltman 1995). Therefore, one might suggest that the addition of strength training to concurrent endurance training interferes with submaximal endurance (peripheral adaptations) but does not affect the development of $\dot{V}O_{2\,max}$ (central adaptations).

After large initial increases during the 2 weeks of strength training, a plateau phase in maximal dynamic strength development was observed during the last 4 weeks of training in the ST group (Fig. 2). This plateau occurred much earlier than in previous studies performed with adult men (Häkkinen et al. 1985) or women (Häkkinen et al. 1990). Although the absence in the present study of a control group performing only strength training does not allow us to assess the reason for this plateau phase, it might have several origins as follows:

1. An insufficient strength stimulus and/or lack of variation in the strength training programme (for example, insufficient variability in volume, intensity, frequency or duration) could explain a plateau phase after the large initial increase observed during the first 2 weeks.

2. An interference between concurrent strength and endurance training may have occurred. Several studies have found that the combination of high load strength training with endurance training could compromise optimal gains of strength development while groups who did only weight training showed a linear improvement in strength through the training period (Dudley and Djamil 1985; Hennessy and Watson 1994; Hickson 1980). Therefore, the aerobic nature of handball training might impede further increases of strength when handball training is performed concurrently with high resistance training.

3. The observation that the strength improvement during the last 4 weeks of training was relatively minor may be related to possible effects of overreaching or overtraining, as also indicated by the alterations found in the endocrine response to training. Indeed, in the ST group the plateau phase in strength development occurred concomitantly with a plateau in testosterone:cortisol ratio, whereas a statistically significant increase in testosterone:cortisol ratio occurred in the C group and an increase which approached statistical significance ($P < 0.08$) was observed in the NST group. Decreases (Fry et al. 1993) and increases (Zakas et al. 1994) in testosterone:cortisol ratio after a high-load training period have been found in adolescents and have been associated with overtraining or an enhanced environment for growth, respectively. Therefore, the compromised testosterone:cortisol ratio observed in the ST

group could have reflected an overreaching or overtraining state and could explain why the improvement in maximal strength was compromised during the last 4 weeks of training.

We can only speculate on the possible mechanisms by which overreaching or some kind of overtraining might occur in the ST group. It has been shown that prolonged heavy-resistance strength training (≥80% of 1-RM) may be very stressful and overstrain the nervous and the endocrine systems (Häkkinen 1994). An alternative explanation could be related to the increased total frequency and volume of training in the ST group (seven to eight training sessions per week) compared with the NST and C groups (five to six training sessions per week). The high load of training in the ST group might elicited an excessive endocrine demand in 14–16 year-old adolescents.

This demand can easily become more excessive in a young population than in adults, because adolescents have been shown to have an immature hypothalamic – pituitary – gonadal axis (i.e. reflected by lower circulating concentrations of testosterone, luteinizing hormone, and follicle stimulating hormone; Martha et al. 1989; Minuto et al. 1988), and because they have an higher endocrine demand to support normal growth (reflected by greater circulating concentrations than adults of growth hormone and somatomedin-C; Martha et al. 1989; Minuto et al. 1988). In this hypothesis the excessive endocrine response induced by the high training load might have compromised the positive integration of growth, training and maturation that occurs in adolescents when lower training loads are employed (Zakas et al. 1994).

In summary, it has been shown that handball places special demands on explosive strength production of the leg and arm extensor muscles and on aerobic energy production (Wit et al. 1989). In our study, the addition of heavy-resistance strength training interfered with optimal gains in endurance and dynamic explosive characteristics in the legs. Therefore, it is suggested that this type of heavy strength-training regime has a negative influence on the ability to play handball. However, the role of maximal strength training for the arms may be important for strength development because a significant increase in throwing velocity was observed in the ST group. Further research including power training (i.e. a type of training in which the loads are lower than in heavy resistance training but the contraction velocities are much higher) or a combination of strength and power training is needed to show if there is some strength training regime that can increase maximal and explosive strength without interfering with the development of endurance.

References

Andersen JL, Bangsbo J, Klitbaard H, Saltin B (1992) Changes in short-term performance and muscle fibre composition by strength training of elite soccer players. J Sports Sci 10:162

Aunola S, Marniemi J, Alanen E, Mantyla M, Saraste M, Rusko H (1988) Muscle metabolic profile and oxygen transport capacity as determinants of aerobic and anaerobic thresholds. Eur J Appl Physiol 57:726–734

Drinkwater DT, Ross W (1980) Anthropometric fractionation of body mass. In: International Seminar on Kinanthropometry, 2d, Katholieke Universiteit te Leuven, 1978

Dudley GA, Djamil R (1985) Incompatibility of endurance and strength training modes of exercise. J Appl Physiol 59:1446–1451

Enoka RM (1988) Muscle strength and its development. New perspectives. Sports Med 6:146–168

Fry AC, Kraemer WJ, Stone MH, Warren BJ, Kearney JT, Maresh CM, Weseman CA, Fleck SJ (1993) Endocrine and performance responses to high volume training and amino acid supplementation in elite junior weightlifters. Int J Sport Nutrition 3:306–322

Häkkinen K (1988) Effects of the competitive season on physical fitness profile in elite basketball players. J Hum Mov 15:119–128

Häkkinen K (1989) Maximal force, explosive strength and speed in female volleyball and basketball players. J Hum Mov Stud 16:291–303

Häkkinen K (1993) Changes in physical fitness profile in female volleyball players during the competitive season. J Sports Med Phys Fitness 33:223–232

Häkkinen K (1994) Neuromuscular adaptation during strength training, aging, detraining and immobilization. Crit Rev Phys Rehab Med 6:161–198

Häkkinen K, Komi PV (1983) Alterations of mechanical characteristics of human skeletal muscle during strength training. Eur J Appl Physiol 50:161–172

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

Häkkinen K, Alen M, Komi PV (1985) Changes in isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of human skeletal muscle during strength training and detraining. Acta Physiol Scand 125:573–583

Häkkinen K, Komi PV, Kauhanen H (1987) Scientific evaluation of specific loading of the knee extensors with variable resistance, isokinetic and barbell exercises. Med Sport Sci 26:224–237

Häkkinen K, Pakarinen A, Kyrolainen H, Cheng S, Kim DH, Komi PV (1990) Neuromuscular adaptations and serum hormones in females during prolonged power training. Int J Sports Med 11:91–98

Hennessy LC, Watson AWS (1994) The interference effects of training for strength and endurance simultaneously. J Strength Condit Res 8:12–19

Hickson RC (1980) Interference of strength development by simultaneously training for strength and endurance. Eur J Appl Physiol 45:255–269

Hoff J, Almasbakk B (1995) The effects of maximum strength training on throwing velocity and muscle strength in female team-handball players. J Strength Condit Res 9:255–258

Janz KF, Golden JC, Hansen JR, Mahoney LT (1992) Heart rate monitoring of physical activity in children and adolescents. The Muscatine study. Pediatrics 89:256–261

Kraemer WJ, Fleck SJ (1993) Strength training for children: the controversy resolved. Strength training for young athletes-Human Kinetics, Champaign, I11., pp 1–9

Komi PV, Bosco C (1978) Utilization of stored elastic energy in leg extensor muscles by men and women. Med Sci Sports 10:261–265

Lafontaine TP, Londeree BR, Spath WK (1981) The maximal steady state versus selected running events. Med Sci Sports Exerc 13:190–192

Malina RM, Bouchard C (1991) Physical activity as a factor in growth, maturation, and performance. Growth, maturation, and physical activity. Human Kinetics, Champaign, I11., pp 371–390

Marcinik EJ, Potts J, Shlabach G, Will S, Dawson P, Hurley BF (1991) Effects of strength training on lactate threshold and endurance performance. Med Sci Sports Exerc 23:739–743

Martha PM, Rogol AD, Veldhuis JD, Kerrigan JR, Goodman DW, Blizzard RM (1989) Alterations in the pulsatile properties of circulating growth hormone concentrations during puberty in boys. J Clin Endocrinol Metab 69:563–570

Mero A, Häkkinen K, Kauhanen H (1989) Hormonal profile and strength development in young weight lifters. J Hum Mov Stud 16:255–266

Minuto F, Barreca A, Del Monte P, Fortini P, Resentini M, Morabito F, Giordano G (1988) Spontaneous growth hormone and somatomedin- C/insuline-like growth factor -I secretion in obese subjects during puberty. J Endocrinol Invest 11:489–495

Ozmun JC, Mikesky AE, Surburg PR (1994) Neuromuscular adaptations following prepubescent strength training. Med Sci Sports Exerc 26:510–514

Paavolainen L, Häkkinen K, Rusko H (1991) Effects of explosive type strength training on physical performance characteristics in cross-country skiers. Eur J Appl Physiol 62:251–255

Ramsay JA, Blimkie CJR, Smith K, Garner S, Macdougall JD, Sale DG (1990) Strength training effects in prepubescent boys. Med Sci Sports Exerc 22:605–614

Ross WD, Marfell-Jones MJ (1991) Kinanthropometry. In: McDougall JD, Wenger HA, Green HJ (eds) Physiological testing of the high-performance athlete. Human Kinetics, Champaign, Il, pp 223–308

Rusko H, Bosco C (1987) Metabolic response of endurance athletes to training with added load. Eur J Appl Physiol 56:412–418

Viitasolo, JT (1988) Evaluation of explosive strength for young and adult athletes. Res Q 59:9–13

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

Weltman A (1995) The blood lactate response to exercise. In: Current issues in exercise science. Monography no. 4. Human Kinetics, Champaign, I11, pp 1–117

Williams D (1993) Overview of skeletal injuries in youth sports. Sports Med 15:38–42

Winegard K, Hicks A, Sale D, Vandervoort A (1996) A 12-year follow-up study of ankle muscle function in older adults. J Gerontol Biol Sci 51ª:B202–B207

Wit A, Eliasz J, Janiak J, Wit B, Viitasalo J (1989) Modifications de la puissance du train inférieur des handballeurs au cours du match. Sci Motr 8:13–17

Zakas A, Mandroukas K, Karamouzis M, Panagiotopoulou G (1994) Physical training, growth hormone and testosterone levels and blood pressure in prepubertal, pubertal and adolescent boys. Scand J Med Sci Sports 4:113–118