Effects of 8-Week in-Season Upper and Lower Limb Heavy Resistance Training on The Peak Power, Throwing Velocity, and Sprint Performance of Elite Male Handball Players

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Abstract

Hermassi, S, Chelly, MS, Tabka, Z, Shephard, RJ, and Chamari, K. Effects of 8-week in-season upper and lower limb heavy resistance training on the peak power, throwing velocity, and sprint performance of elite male handball players. *J Strength Cond Res* 25(9): 2424–2433, 2011—The aims of this study were to test the potential of in-season heavy upper and lower limb strength training to enhance peak power output (W_{peak}), vertical jump, and handball related field performance in elite male handball players who were apparently already well trained, and to assess any adverse effects on sprint velocity. Twenty-four competitors were divided randomly between a heavy resistance (HR) group (age 20 $\pm$ 0.7 years) and a control group (C; age 20 $\pm$ 0.1 years). Resistance training sessions were performed twice a week for 8 weeks. Performance was assessed before and after conditioning. Peak power (W_{peak}) was determined by cycle ergometer; vertical squat jump (SJ) and countermovement jump (CMJ); video analyses assessed velocities during the first step (V_{1S}), the first 5 m (V_{5m}), and between 25 and 30 m (V_{peak}) of a 30-m sprint. Upper limb bench press and pull-over exercises and lower limb back half squats were performed to 1-repetition maximum (1RM). Upper limb, leg, and thigh muscle volumes and mean thigh cross-sectional area (CSA) were assessed by anthropometry. W_{peak} (W) for both limbs ($p < 0.001$), vertical jump height ($p < 0.01$ for both SJ and CMJ), 1RM ($p < 0.001$ for both upper and lower limbs) and sprint velocities ($p < 0.01$ for V_{1S} and V_{5m}; $p < 0.001$ for V_{peak}) improved in the HR group. Upper body, leg, and thigh muscle volumes and thigh CSA also increased significantly after strength training. We conclude that in-season biweekly heavy back half-squat, pull-over, and bench-press exercises can be commended to elite male handball players as improving many measures of handball-related performance without adverse effects upon speed of movement.

Key Words Maximal strength, upper extremity, lower extremity, throwing performance, vertical jump, muscle volumes

Introduction

Handball is a strenuous contact sport that places emphasis on running, jumping, sprinting, throwing, hitting, blocking, and pushing (14). In addition to technical and tactical skills it has been argued that muscular strength and power are the most important factors that give a clear advantage in elite competitions (30). Appropriate anthropometric characteristics and handball throwing ability are also important to success (15). Despite the increase in professionalization of this sport, there is a paucity of research on the performance characteristics of elite players, and few data are available for handball players over an entire season. Because of the increased demands of technical training and competition, in-season strength and conditioning have been proposed to maintain adequate levels of strength and power over the playing season (7,30). Although handball playing in itself can enhance many of these factors, elite competitors must engage in additional handball-specific conditioning, including exercises to develop high-intensity intermittent aerobic effort, speed, agility, strength, and power (7,30); a combination of speed and explosive strength training are needed to improve peak running speed and jump height (8,10) and bouts of high-intensity running are needed to develop maximal anaerobic

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power and explosive capacity (6,7,33). Studies in volleyball players indicated to Häkkinen et al. (20) that to maintain explosive strength, the extent of both strength and explosive training should be carefully monitored throughout the competitive season. Decrements in both maximal strength and explosive strength were observed if explosive strength training was maintained but heavy resistance (HR) training was stopped for as little as 5.5 weeks (19), highlighting the importance of continued strength training during the competitive season. These observations suggest that in handball, also, specific in-season conditioning, sprint and power training should be supplemented by resistance exercise (23). However, little is known about the most appropriate regimen, and concerns remain that if in-season HR work is combined with sport-specific training, the several components of the training program may interfere with each other (18,21,23).

Specific studies of this issue have examined the influence of speed-strength programs on throwing velocity (25), or the relationship between throwing velocity and isokinetic strength (3,12), rather than the impact on jumping ability, sprint performance, and maximal dynamic strength. Information on training methods that increase throwing ability is also limited, and most of the research to date has been conducted in other sports such as baseball (32,35). Handball coaches and scientists agree that the main determinants of throwing velocity are: technique, the timing of movement in consecutive body segments and the strength and power of the upper and lower limbs (15). Each of these factors can be improved by appropriate training, particularly resistance programs. Chelly et al. (9) previously highlighted the contribution of the lower limbs to throwing ability, underlining that coaches should include strength and power programs not only for the shoulders and arms, but also for the lower limbs. Biweekly training of this type seems sufficient to induce substantial gains not only in peak power output and dynamic strength, but also in handball throwing velocity (22).

We thus hypothesized that elite handball players who supplemented their normal in-season handball training with an 8-week program of heavy biweekly resistance exercises for both the lower and the upper limbs would enhance their muscular strength and power without compromising other factors critical to handball performance (throwing velocity, sprinting, and jumping abilities).

Methods

Experimental Approach to the Problem

This study addressed the question: Can 8 weeks of biweekly HR in-season training enhance the muscular strength and power of elite handball players relative to a standard conditioning regimen, without compromising other critical aspects of the individual's performance such as throwing velocity, sprinting and jumping abilities? A team of experienced players ($n = 24$) was randomly divided between HR ($n = 12$) and control (standard in-season regimen) (C; $n = 12$) groups (Table 1). Participants completed 2 familiarization trials in the 2 weeks before testing. Specific measurements began 4 months into the playing season; data were collected before starting the additional training, and immediately after the 8-week trial; on both occasions, data were collected at the same time of day, and at least 3 days after the most recent competition. Players maintained their normal intake of food and fluids, but abstained from physical exercise for 1 day before testing, drank no caffeine-containing beverages for 4 hours before testing, and ate no food for 2 hours before testing. Strong verbal encouragement ensured maximal effort throughout all measurement and resistance training sessions. The protocol included cycle-ergometer force–velocity testing of upper and lower limb power, vertical countermovement jump (CMJ) and squat jump (SJ) to assess leg power, leg force, jump velocity and jump height, a handball throwing test, 1 repetition maximum bench press ($1RM_{BP}$), 1RM pull-over ($1RM_{PO}$), and 1RM half-back squat ($1RM_{HS}$). The muscle volumes of the upper and lower limbs were also estimated anthropometrically.

Subjects

Procedures were approved by the Institutional Ethics Review Committee in accordance with the current national and international laws and regulations governing the use of human subjects. Before participating in the study, the subjects were fully informed about the protocol, and a written informed consent was obtained from each subject before testing. Subjects were free to withdraw from the study without penalty at any time. A questionnaire regarding medical history, age, height, body mass, training characteristics, injury history, team handball experience, and performance level was completed before participation. An initial examination by the team physician focused on orthopedic and other conditions that might preclude resistance training; all participants were found to be in good health. The subjects, 24 elite, national-level male handball players (age 21 ± 1.9 years, height 1.83 ± 0.08 m, body mass 81 ± 12 kg, body fat

Table 1. Physical characteristics of study participants. *

	Heavy resistance group (n =12)	Control group (n = 12)
Age (y)	22.1 ± 1.7	20.2 ± 1.5
Body mass (kg)	81.1 ± 14.7	80.5 ± 10.3
Body Height (m)	1.82 ± 0.07	1.84 ± 0.08
% Body fat	13.6 ± 3.2	14.1 ± 7.1
Handball experience (y)	9.1 ± 0.2	8.7 ± 0.6

*Values are given as mean ± *SD*.

13.2 ± 1.3%, mean handball experience was 8.6 ± 1.3 years), were randomly divided into the experimental (HR) and control (C) groups; these 2 groups were well matched in terms of their initial characteristics.

Evaluation and Procedures

The study was conducted from January to March (8-week period) in the middle of the playing season (from the 22th to the 29th week), commencing in the second preparatory period (after the traditional 8-day winter holiday). Both experimental and control subjects were accustomed to moderate strength training (1 session per week of bench press and half squat exercises at 60% of 1RM loading). All were engaged in the standard training program from the beginning of the competitive season (September) until the end of the study (March). This regimen comprised handball training 3–4 times per week, and one official game per week. Practice training sessions lasted ~90 minutes; usually, they emphasized skilled activities at various intensities, offensive and defensive strategy, and some ~30 minutes of continuous play. During the 8 week study, the experimental group supplemented this regimen by HR training twice per week.

All participants were evaluated before and after the 8-week trial. Tests were completed in a fixed order over 3 consecutive days; experimental subjects were evaluated 5–9 days after their last resistance training session, to allow adequate recovery from any acute effects of their training.

Testing Schedule

Subjects were familiarized with circuit training, lifting and 1RM test procedures for 2 weeks before definitive measurements began. A pretest 1RM determined the approximate 1RM value. A standardized battery of warm-up exercises was performed before maximal efforts.

On the first test day, the force–velocity test was performed (using first the lower and then the upper limbs), followed by the anthropometric assessment, and finally the Squat and CMJs. On the second day, $1RM_{PO}$, $1RM_{BP}$, and sprint performance were assessed. On the third day, the ball throwing velocity and $1RM_{HS}$ were determined.

Day 1

The Force–Velocity Test. Force–velocity measurements for the lower limbs were performed on a standard Monark cycle ergometer (model 894 E, Monark Exercise AB, Vansbro, Sweden) as detailed elsewhere (5,9). In brief, the instantaneous maximal pedaling velocity during a 7-second all-out sprint was used to calculate the maximal anaerobic power for each braking force, and the subject was judged to have reached peak power (W_{peak}) if an additional load induced a decrease in power output. Arm tests were made using an appropriately modified cycle ergometer (5,9). The parameters measured included W_{peak}, maximal pedaling force for upper and lower limbs (F_{0UL} and F_{0LL}, respectively) and maximal pedaling velocity for upper and lower limbs (V_{0UL} and V_{0LL}, respectively) (39).

Arm tests began with a braking force equal to 1.5% of the subject's body mass (5, 9). After a 5-minute recovery, the braking was increased in sequence to 2, 3, 4, 5, 6, 7, 8, and 9% of body mass. For more details of the force–velocity tests, see Chelly et al. (9).

Anthropometry. Circumferences and skinfold thickness at different levels of the thigh and the calf, the arm and the forearm, the length of the lower and upper limb, and the breadth of the humeral and femoral condyles were measured to estimate the muscle volume of the upper and lower limbs, as described previously (9,24).

Standard equations predicted the percentage of body fat from measurements of biceps, triceps, subscapular, and suprailiac skinfolds (41):

$$\%\text{Body fat} = a \log\left(\sum 4\text{folds}\right) - b,$$

where $\sum S$ is the sum of the 4 skinfolds (in mm), and a and b are constants dependent on sex and age.

The mean thigh cross-sectional area (CSA) was calculated from the maximal and mid thigh circumferences according to the formula:

$$\text{Circumference}(C) = 2p \cdot \text{Radius}(R),$$

$$R = C/2p.$$

Squat Jump and Countermovement Jump. Characteristics of the SJ and the CMJ (jump height, maximal force before take-off, maximal velocity before take-off and the average power of the jump) were determined using a force platform (Quattro Jump, version 1.04, Kistler Instrument AG, Winterthur, Switzerland). Jump height was determined as the center of mass displacement, calculated from the recorded force and body mass. Subjects began the SJ at a knee angle of 90°, avoiding any downward movement, and they performed a vertical jump by pushing upwards, keeping their legs straight throughout. The CMJ was begun from an upright position, making a rapid downward movement to a knee angle of ~90° and simultaneously beginning to push-off. One minute of rest was allowed between the 3 trials of each test, the highest jump being used in subsequent analyses.

Day 2

One Repetition maximum Pull-Over. The bar was positioned 0.2 m above the subject's chest and was supported by the bottom stops of the device. The player performed successive eccentric–concentric contractions from the starting position. A full description of the pull-over exercise used in this investigation is provided by Chelly et al. (9). All subjects were familiar with the required technique, having used it in their weekly training sessions. A pretest assessment of $1RM_{PO}$ was made during the final standard training session. For RM_{PO} as for the RM_{BP} (see below), warm-up for the definitive test comprised 5 repetitions at loads of 40–60% of the pretest

Table 2. Details of heavy resistance training program followed by heavy resistance group over 8 consecutive weeks (2 sessions per week).*

Exercises	Session 1	Session 2	Session 3	Session 4	Session 5	Session 6
Bench press	80: 3 × 3	80: 3 × 5	85: 3 × 3	85: 3 × 3	85: 3 × 5	85: 3 × 5
Pull-over	80: 3 × 3	80: 3 × 5	85: 3 × 3	85: 3 × 3	85: 3 × 5	85: 3 × 5
Half-back squat	80: 3 × 3	80: 3 × 4	85: 3 × 3	85: 3 × 4	85: 3 × 6	85: 3 × 6
Exercises	Session 7	Session 8	Session 9	Session 10	Session 11	Session 12
Bench press	90: 3 × 2	90: 3 × 3	90: 3 × 4	90: 3 × 5	95: 3 × 2	95: 3 × 2
Pull-over	90: 3 × 2	90: 3 × 3	90: 3 × 4	90: 3 × 5	95: 3 × 2	95: 3 × 2
Half-back squat	90: 3 × 3	90: 3 × 4	90: 3 × 5	90: 3 × 6	95: 3 × 3	95: 3 × 3
Principal exercises: % of RM: Sets × Reps	Session 13	Session 14	Session 15	Session 16		
Bench press	95: 3 × 3	95: 3 × 3	95: 3 × 4	95: 3 × 4		
Pull-over	95: 3 × 3	95: 3 × 3	95: 3 × 4	95: 3 × 4		
Half-back squat	95: 3 × 4	95: 3 × 4	95: 3 × 5	95: 3 × 5		
Training summary						
Principal exercises	% Percent of RM		Sets × reps			

*RM = repetition maximum.

RM_{PO} and RM_{BP}. Thereafter, 4–5 separate attempts were performed until the subject was unable to extend the arms fully on 2 occasions. The load noted at the last acceptable extension was considered as the $1RM_{PO}$. Two minutes of rest was allowed between trials.

One Repetition Maximum Bench Press. The maximal strength of the upper extremity was assessed using a maximum 1 repetition successive eccentric–concentric bench press action 1RM bench press ($1RM_{BP}$). Bench press (elbow extension) was chosen because it involves arm muscles specific to overhand throwing (9,29). The test was performed in a squatting apparatus; the barbell was attached at both ends, and linear bearings on 2 vertical bars allowed only vertical movements. The bar was positioned above the subject's chest (about 0.3 m) and supported by the bottom stops of the measuring device. The subject performed successive elbow flexion extensions from the starting position. A full description of the bench press is provided by Chelly et al. (9).

Sprint Running Performance. After familiarization, subjects made a maximal 30-m sprint on an outdoor tartan surface. Players rarely run >30 m during a handball match. Thus, we chose the sprint phase between 25 and 30 m to indicate the maximal running velocity for our players. Body displacement was filmed by 2 cameras (Sony Handycam, DCR-PC105E, Tokyo, Japan; 25 frames per second) placed at a distance of 10 m perpendicular to the running lane. The first camera filmed the individual over the first 5 m, and a second camera monitored the sprint between 25 and 30 m. Participants performed 2 trials, separated by an interval of 5 minutes. Appropriate software (Regavi and Regressi; Micrelec, Coulommiers, France) converted measurements of hip displacement to the corresponding velocities: the first step after the start (V_{1S}), the first 5 m (V_{5m}), and between the 25 and 30 m (V_{peak}). The reliability of the camera and the data processing software has been checked previously (8).

Table 3. Intraclass correlation coefficients showing the reliability of various measures of ball-throwing velocities, track running velocities, 1RM scores for upper and lower limbs and jumping tests.*

	ICC	95% CI
Ball-throwing velocities		
Jumping shot	0.91	0.80–0.96
3-Step running throw	0.97	0.93–0.98
Standing throw	0.94	0.88–0.97
Track running velocities		
Velocity for first step after start	0.93	0.85–0.97
Velocity over first 5 m	0.97	0.91–0.98
Peak sprint velocity	0.97	0.91–0.98
1RM strength of upper and lower limbs		
1RM half-back squat	0.92	0.82–0.96
1RM pull-over	0.97	0.81–0.96
1RM bench press	0.90	0.80–0.96
Jumping tests		
Squat jump	0.98	0.92–0.98
Countermovement jump	0.95	0.81–0.96

*1RM = 1 repetition maximum; ICC = intraclass correlation coefficient; CI = confidence interval.

TABLE 4. Comparison of muscle volumes of upper and lower limbs between heavy resistance and control groups before and after 8-week trial.*†

	Heavy resistance group		Control group	
	Before	After	Before	After
Upper limb muscle volume (L)	3.62 ± 0.92	3.97 ± 1.0‡	3.01 ± 0.59	3.01 ± 0.60
Leg muscle volume (L)	10.9 ± 1.9	11.6 ± 1.9§	9.8 ± 1.9	9.8 ± 1.9
Thigh muscle volume (L)	8.0 ± 1.5	8.7 ± 1.5§	7.2 ± 1.7	7.1 ± 1.7
Cross *sectional area* (cm^2)	192 ± 26	208 ± 26§	183 ± 32	181 ± 31

*Values are given as mean ± *SD.*
†A 2-way analysis of variance (group × time) assessed the statistical significance of training related effects for Tables 4–7.
‡$p < 0.01$.
§$p < 0.001$.

Day 3

Handball Throwing. Specific explosive strength was evaluated by making 3 types of overarm throw on an indoor handball court: a standing (penalty) throw), a 3-step running throw and a jump shot. The standing and 3-step throws have been described by Hermassi et al. (22). In the jump shot, players made a preparatory 3 step run before jumping vertically and releasing the ball while in the air, behind a line 9 m from the goal. Throwing times were recorded by digital video camera (Sony Handycam DCR-PC105E, Tokyo, Japan), positioned on a tripod 3 m above and parallel to the player. Data processing software (Regavi and Regressi, Micrelec) converted measures of ball displacement to velocities. Throws with the greatest starting velocity were selected for further analysis. The reliability of the data processing software has been verified previously (8); measurements were accurate to 0.001 seconds, and the test–retest coefficient of variations in throwing velocity was 1.9%.

One Repetition maximum Back Half-Squat at 90°. Participants maintained an upright position. The bar was grasped firmly with both hands and was also supported on the shoulders.

TABLE 5. Force–velocity test scores for upper and lower limbs in heavy resistance and control groups before and after the 8-week trial.*†

	Heavy resistance group		Control group	
	Before	After	Before	After
Upper limb				
Power (W)	477 ± 98	532 ± 87‡	522 ± 113	521 ± 123
Power ($W \cdot kg^{-1}$)	6.1 ± 1.1	6.7 ± 1.1‡	6.7 ± 2.0	6.6 ± 2.1
Power ($W \cdot L^{-1}$)	138 ± 38	140 ± 35	178 ± 45	177 ± 45
V_{OUL} (rpm)	133 ± 19	149 ± 19	149 ± 11	166 ± 21
F_{OUL} (N)	118 ± 25	140 ± 15	120 ± 20	141 ± 12
Lower limb				
Power (W)	681 ± 122	763 ± 121‡	844 ± 165	841 ± 153
Power ($W \cdot kg^{-1}$)	8.7 ± 1.3	9.7 ± 1.3‡	10.7 ± 3.1	10.6 ± 3.0
Power (W/total leg·muscle·volume)	64 ± 13	67 ± 13§	88 ± 18	88 ± 19
Power (W/thigh·muscle·volume)	87 ± 17	90 ± 16	122 ± 27	123 ± 28
V_{OLL} (rpm)	191 ± 21	202 ± 16	198 ± 12	210 ± 11
F_{OLL} (N)	133 ± 16	155 ± 24	138 ± 17	157 ± 17

*V_{OUL} = maximal pedaling velocities for upper limbs; V_{OLL} = maximal pedaling velocities for lower limbs; F_{OUL} = maximal braking forces for upperlimbs; F_{OLL} = maximal braking forces for lower limbs.
†Values are given as mean ± *SD.*
‡$p < 0.001$.
§$p \leq 0.05$.

Table 6. Vertical jump test performance of heavy resistance and control groups before and after 8-week trial.*

	Heavy resistance group		Control group	
	Before	After	Before	After
Squat jump				
Power (W)	3,056 ± 420	3,523 ± 512†	3,279 ± 596	3,083 ± 578
Power (W·kg^{-1})	39.0 ± 2.7	44.3 ± 1.5†	40.3 ± 2.5	37.5 ± 2.2
Velocity (m·s^{-1})	1.8 ± 0.2	1.7 ± 0.1	1.9 ± 0.1	2.0 ± 0.3
Force (N)	1,814 ± 375	1,733 ± 631	1,792 ± 238	1,724 ± 220
Height (m)	0.39 ± 0.03	0.44 ± 0.02‡	0.40 ± 0.03	0.38 ± 0.02
Countermovement jump				
Power (W)	2,096 ± 559	2,165 ± 381	2,201 ±379	2,180 ± 376
Power (W·kg^{-1})	26.4 ± 4.9	27.3 ± 3.3	27.2 ± 3.3	26.7 ± 2.9
Velocity (m·s^{-1})	2.0 ± 0.2	1.9 ± 0.1	2.1 ± 0.2	1.2 ± 0.3
Force (N)	1,684 ± 324	1,729 ± 295‡	1,721 ± 250	1,673 ± 219
Height (m)	0.43 ± 0.02	0.48 ± 0.02	0.44 ± 0.02	0.42 ± 0.02

*Values are given as mean ± *SD*.
†$p < 0.001$.
‡$p < 0.01$.

The knees were bent to ~90° and the subject then regained the upright position, with the legs fully extended. After 2 successful repetitions at the pretest 1RM, a further 1-kg load was added. If the second repetition could not be completed at the new loading, this value was accepted as the individual's 1RM. A full description of the exercise has been provided by Chelly et al. (8).

Training. The HR program continued for 8 weeks. Biweekly sessions were held on Tuesdays and Thursdays, immediately before normal handball training. $1RM_{BP}$ and $1RM_{PO}$ exercises determined appropriate training loads. 1RM Back Half-Squat at 90 ($1RM_{BHS}$), $1RM_{BP}$, and $1RM_{PO}$ values for the HR group were reassessed after 4 weeks, with appropriate updating of loads.

Table 7. Sprint velocities for the first step, first 5 m, and maximal sprinting, ball-throwing velocities and 1RM strength measurements for heavy resistance and control groups before and after 8-week trial.*†

	Heavy resistance group		Control group	
	Before	After	Before	After
Track running velocities (m·s^{-1})				
First step	3.14 ± 0.27	3.55 ± 0.34‡	3.67 ± 0.35	3.47 ± 0.33
First 5 m	5.28 ± 0.27	5.88 ± 0.28‡	6.18 ± 0.41	5.88 ± 0.28
Peak sprinting	9.8 ± 0.7	10.6 ± 0.5§	11.6 ± 1	11.2 ± 0.9
Ball-throwing velocities (m·s^{-1})				
Jumping shot	30.1 ± 3.5	35.4 ± 2.8§	32.2 ± 2.3	31.0 ± 2.3
3-Step running throw	31.9 ± 2.7	38.1 ± 1.8§	35.7 ± 2.6	35.1 ± 3.1
Standing throw	29.4 ± 2.7	34.6 ± 1.2§	31.7 ± 3.2	28.8 ± 3.2
1RM lower and upper limb strength (kg)				
1RM half-back squat	181 ± 11	198 ± 9§	186 ± 11	181 ± 5
1RM pull-over	29.3 ± 3.3	39.1 ± 2.6§	28.3 ± 5.0	30.8 ± 2.5
1RM bench press	80.4 ± 5.0	96.2 ± 3.6§	80.7 ± 5.3	79.4 ± 5.4

*1RM = 1 repetition maximum.
†Values are given as mean ± *SD*.
‡$p < 0.01$.
§$p < 0.001$.

Each HR training session included 2 exercises for the upper extensor muscles (pull-over and bench press) and half-squat exercises to strengthen the lower limbs. Subjects trained at 80–95% of their personal 1RM, performing 1–3 repetitions per set and 3–6 sets of each exercise, with 3- to 4-minute rest between sets (Table 2). Pull-over, bench press and half-squat exercises all require successive eccentric–concentric contractions performed at a slow velocity, this pattern of training being designed to maximize increases in strength (28).

Statistical Analyses

Standard statistical methods were used to calculate means and *SD* s. Training effects were assessed by a 1-way analysis of variance with repeated measure (group × time). If a significant *F* value was observed, Sheffé's post hoc procedure was used to locate significant pairwise differences. The reliability of throwing ball velocities, $1RM_{HS}$, $1RM_{BP}$, $1RM_{PO}$ and jump tests was assessed using intraclass correlation coefficients (Table 3). Statistical significance was set throughout at $p \leq 0.05$.

Results

The Control Group did not show any significant changes in power, track performance or anthropometric characteristics over the 2-month trial.

In the HR group, the 8 weeks of strength training induced significant increases in muscle volume (total leg and thigh, $p < 0.001$ for both measures; upper limb, $p < 0.01$) (Table 4). Thigh CSA measures showed a parallel increase ($p < 0.001$).

The peak power of both upper and lower limbs increased relative to that of control subjects (Table 5), but V_{0UL}, F_{0UL}, V_{0LL}, and F_{0LL} remained unchanged. SJ and CMJ height performances also increased relative to controls ($p < 0.01$) (Table 6).

The increase of lower limb peak power was accompanied by faster running velocities ($p < 0.01$ for V_{1S} and V_{5m}; $p < 0.001$ for V_{peak}) (Table 7); there were also significant gains in all types of throwing ($p < 0.01$) (Table 7) and in 1RM strength for both the upper and lower limbs ($1RM_{HS}$, $1RM_{BP}$, $1RM_{PO}$) ($p < 0.001$ for all measurements) (Table 7).

Discussion

The primary aims of this study were to determine whether elite male handball players could enhance muscle strength and power by an in-season program of HR training for the upper and the lower limbs, and whether gains could be realized without detriment to other aspects of performance. The answer to both of these questions is strongly positive; our results substantiate our hypothesis that HR biweekly in-season training enhances the peak power output of both upper and lower limbs, whether assessed by jumping or sprinting, a cycle ergometer force–velocity test, or throwing velocity. Moreover, there are concomitant gains of muscle volume and 1RM strength, and no evidence that the development of speed has compromised the speed of the players.

Other studies have examined the effects of concentric exercise on the power and ball throwing velocity of handball players (14,16,22,30), but this is the first study to examine gains of jumping and sprinting performance, using successive eccentric–concentric heavy load exercises such as the pull-over and the bench-press for the upper body and half-squat exercises for the lower limbs.

The HR group showed gains of power, both absolute (W) (11.5%; $p < 0.001$) and relative to body mass ($W \cdot kg^{-1}$) (9.8%; $p < 0.001$) in the upper limbs, but no change when power was expressed per liter of muscle volume (Table 5). This suggests that despite the relatively short period of training, gains were attributable largely to an increase of regional muscle volume (22,37). There were also considerable gains of both absolute (W) (12%; $p < 0.001$) and relative muscle power ($W \cdot kg^{-1}$) (11.5%; $p < 0.001$) in the lower limbs, but in this case some gains remained even when expressed per unit of muscle volume (Table 5). Nevertheless, when W_{peak} was expressed relatively to thigh muscle volume, the difference between HR (3.5%) and C (1.5%) was no longer statistically significant, suggesting that again, most of the gains seen in the lower limbs were attributable to development of the thigh muscles. This presumably reflects the introduction of heavy-resistance training to players already adapted to more moderate resistance training. Schmidtbleicher (37) defined power as the greatest impulse the neuromuscular system could produce in a given time. The application of heavy loading is fundamental to power development, demanding maximal motor unit recruitment according to the 'size principle,' with units also firing at higher frequencies (4,31). The development of large forces may also initiate force-feedback reflexes from the Golgi tendon organs or improve the synchronization of motor unit firing (17,26,37). In terms of muscle hypertrophy, large forces are important for remodeling of the tissue through protein synthesis and degradation (13). Receptors and membrane sensitivities are stimulated, and muscle growth factors are released, triggering both an increase in protein turnover and the accretion of muscle protein (11). In this context, reversible tissue damage induced by active stretching (as performed by the present subjects during their training) seems an important stimulus to hypertrophy.

However, competitive performance in handball depends not only on strength, but also on the ability to exert force at the speed required by this discipline. In the present study, longer contraction durations were associated with heavier loads; such a prescription seems best suited to maximizing strength (28). Many authors have replicated the finding of Gorostiaga et al. (16) that whereas specific resistance training improves the strength of both the upper extremity muscles (23%; $p < 0.01$) and the leg extensors (12.2%; $p < 0.01$), no gains can be anticipated from low resistance forms of activity such as team handball practice. In the present study, gains for the upper limbs (HR: 33.5 and 20% for pull-over and bench press, respectively) were even larger than those previously observed by Gorostiaga et al. (16), possibly because of differences in the initial status of the players or the training exercises that were undertaken. Gorostiaga et al. (14) studied the effects of an entire 45-week season on power–load relationships for the arm extensors of elite male handball players. They examined performance on 4 occasions: during the first preparatory period (T1), at the beginning (T2) and the end (T3) of the first competitive period, and at the end of the second competitive period (T4). Training was periodized from an initial high-volume, low-intensity phase to a low-volume, high-intensity phase nearer competition. The $1RM_{BP}$ values at T3 were increased significantly ($p < 0.01$) relative to T1 (14). Their findings are in general agreement with the present data, because we noted a significant enhancement ($p < 0.001$) of both $1RM_{PO}$ and $1RM_{BP}$. The greater increase of 1RM upper limb strength in this study could be explained by the heavier loadings adopted during our resistance training sessions (28,30), or the fact that Gorostiaga et al. (14) were studying athletes with a greater initial training level (37). Marques and González-Badillo (30) also noted a 28% increase of $1RM_{BP}$, after 12 weeks of resistance training (2–3 sessions per week) in high level handball players, close to the 33.5% gain of $1RM_{BP}$ that we observed; their loadings were in the range 70–85% of concentric $1RM_{BP}$.

Vertical jumping is frequent in both defensive (e.g., blocking, rebounding, and stealing) and offensive (e.g., passing, rebounding, and shooting) handball maneuvers (42). The classical vertical jump test differs somewhat from handball vertical jumping; nevertheless, this study showed gains in vertical jump height (12 and 14% for CMJ and SJ, respectively) similar to those seen during the training of junior soccer players (8) (7.5 and 10% respectively). Christou et al. (10) also found respective gains of 13.5 and 14.4% in the SJ and CMJ of soccer players over 8 weeks of strength training. Gorostiaga et al. (14) are the only previous investigators to have studied the influence of resistance training on the jump performance of handball players. They reported significant increases in a group that had previously engaged only in team practice (6%; $p < 0.001$), but no changes of CMJ in either resistance training or control groups. In contrast, we observed significant (12%; $p < 0.01$) improvements in CMJ height relative to controls, underlining our contention that the introduction of HR training did not interfere with jump development. Weight training on a leg press machine increased SJ performance by +9.1% ($p < 0.01$) [38], in accordance with the present results. Nevertheless, CMJ performance increased only in response to combined training (a weight program on a leg press machine plus jump exercises) (38). This study used a high loading (80–90% of 1RM), which presumably led not only to muscle hypertrophy but also to neuronal adaptations, with an increase in the rate of force development (37). Sale (36) reported increases in electromyographic activity after jump- and weight training, probably because of increased motor unit activation or increased firing frequency. Several factors could contribute to the enhanced CMJ performance that we observed, including the ability to develop greater tension, to activate more contractile elements and to store and reusable elastic energy (38). Alen et al. (1) observed no changes in the jump performance of well-trained power athletes after 24 weeks of heavy squat training, despite large improvements in 1RM squat strength. Baker (2) also found no significant relationship between training-induced changes in 1RM squat performance and vertical jump performance. The likely explanation for the improved jump performance that we observed is that the necessary muscular coordination can only be maximized by using loads that resemble the required skill in terms of movement, speed, and pattern. A heavy general leg exercise such as the squat is relatively more effective for developing intramuscular coordination, whereas loaded SJs are more effective in developing intermuscular coordination.

Sprinting, acceleration, and rapid changes in direction are inherent to both practice and competition in handball. Such efforts depend not only on maximal strength, but also on peak power and agility. There is a velocity-specific effect, and for optimal performance, handball training should simulate the sport movements as closely as possible. Perhaps because of increases in muscle power, our subjects showed increases rather than decreases in all track velocities after the HR training (Table 7), in agreement with a recent study of junior soccer players (8,27). This is the first study to demonstrate this point in handball players.

The HR training also enhanced rather than impaired throwing velocities (Table 7). It is difficult to compare our findings with previous studies of handball players because of differences in study design, methods of measurement (photoelectric cells, radar, cinematography) (12,14,15), age, body mass, skill level (amateur or professional), throwing technique (standing, 3-step running throw, jump shot), and intensity of training. Our results seem in accordance with Gorostiaga et al. (14), who noted a significant enhancement ($p < 0.001$) of standing handball throwing velocity after 6 weeks of heavy upper limb resistance training; however, the training exercises for these authors were the supine bench press, half squat, knee flexion curl, leg press and pec-dec, quite different exercises from those adopted in the current study. Certainly, our data indicate that a combination of strength, handball technique, and competitive skills training significantly enhanced maximal and specific-explosive strength of the upper extremity over the 8-week program, and this should give players an advantage in throwing, hitting, blocking, pushing, and holding (14,15,22). The increased throwing velocity is likely of major importance to successful play, because elite handball players achieve substantially higher throwing velocities than lower level competitors (an 8–9% advantage in men (14,22) and 10–11% advantage in women (22)).

Using an identical force–velocity protocol, Bouhlel et al. (5) noted significant correlations between javelin performance and the peak power output of both the upper and lower limb muscles. Chelly et al. (9) also found that the peak power of both the upper and the lower limbs were closely correlated with throwing velocity. Critical factors in throwing are transfer of the momentary impulse of power from the lower body to the upper body and then to the ball during its release (34); this ability is closely correlated with competitive performance (40). According to Chelly et al. (9), the greatest part of the total impulse is derived from the powerful muscles of the lower limbs. This assumption is supported by an earlier study of Fleck et al. (12), who noted the greater distance thrown in a set shot, when the feet were in contact with the floor and the lower limbs could be used to increase throwing velocity. Enhancement of throwing velocity in the current study could reflect gains of peak power output in both upper and lower limbs. Neurophysiological mechanisms contributing to the increased throwing velocity remain unclear, Possible factors include not only a selective increase in CSA of the fast-twitch fibers (35), but also more effective neural activation (21), changes in intrinsic muscular properties (21), an increase in myosin–adenosine triphosphatase activity (21), better synchronization of motor units (21), and/or a higher firing frequency.

Practical Applications

This study shows that elite male handball players who consider themselves well-trained can enhance muscle strength and power by undertaking an 8-week biweekly in-season program of HR training involving exercises for both the upper and the lower limbs (bench-press, pull-over and half-squat exercises). Moreover, there is no apparent interference between the development of strength and speed; our data show not only an enhanced peak power output, but also substantial gains in vertical jumping, sprint performance and handball throwing velocity. It has proven quite easy and practical to add the proposed regimen to the traditional in-season technical and tactical training regimen. The performance improvements shown in the present study are of great interest for handball coaches, because the performance of this sport relies greatly on the specific power, jump, sprint and throwing abilities that were enhanced by the high resistance training regimen. Previous authors have found a similar need for deliberate HR training in other sports, but this is demonstrated here for the first time in elite handball players. It is recommended that handball coaches implement in-season HR training to enhance the performance of their players. Potential neuromuscular explanations of the observed gains merit further investigation.

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