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ORIGINAL ARTICLE

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Effects of long-term training specificity on maximal strength and power of the upper and lower extremities in athletes from different sports

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Abstract Maximal concentric one repetition maximum half-squat ($1RM_{HS}$), bench-press ($1RM_{BP}$), power-load curves during concentric actions with loads ranging from 30% to 100% of $1RM_{HS}$ and $1RM_{BP}$ were examined in 70 male subjects divided into five groups: weightlifters (WL, $n=11$), handball players (HP, $n=19$), amateur road cyclists (RC, $n=18$), middle-distance runners (MDR, $n=10$) and age-matched control subjects (C, $n=12$). The $1RM_{HS}$ values in WL, HP and RC were 50%, 29% and 28% greater, respectively, ($P<$ 0.001–0.01) than those recorded for MDR and C. The half-squat average power outputs at all loads examined (from 30% to 100%) in WL and HP ($P<0.001$ at 45% and 60% with HP) were higher ($P<0.05$–0.001) than those in MDR, RC and C. Average power output at the load of 30% of $1RM_{HS}$ in RC was higher ($P<0.05$) than that recorded in MDR and C. Maximal power output was produced at the load of 60% for HP, MDR and C, and at the load of 45% for WL and RC. The $1RM_{BP}$ in WL was larger ($P<0.05$) than those recorded in HP, RC, MDR and C. In the bench press, average muscle power outputs in WL and HP were higher ($P<0.05$–0.001) than those in MDR, RC and C, and were maximized at a load of 30% of 1RM for WL and HP, and at 45% for RC, MDR and C. In addition, the velocities that elicited the maximal power in the lower extremities were lower ($\approx 0.75\ m{\cdot}s^{-1}$) than those occurring in the upper extremities ($\approx 1\ m{\cdot}s^{-1}$). The data suggest that the magnitude of the sport-related differences in strength and/or muscle power output may be explained in part by differences in muscle cross-sectional area, fibre type distribution and in the muscle mechanics of the upper and lower limbs as well as by training background.

Keywords Muscle strength · Force-velocity · Power-velocity

Introduction

The ability of the neuromuscular system to produce maximal power output appears to be critical in many sports such as sprinting, jumping or throwing, sports that require optimal combinations of muscle strength and speed to maximize athletic performance. In the classical concentric force-velocity curve the amount of muscle tension increases with decrease in velocity, reaching the maximal tension in the isometric (i.e. 0 velocity) condition. Under these circumstances maximal power output has been defined to occur at a shortening velocity of approximately 0.3 of the maximal shortening velocity, at a force level of 30% of maximal isometric force and/or between loads of 30%–45% of the one repetition maximum (1RM) (Kaneko et al. 1983; Mastropaolo 1992; Moritani 1993; Faulkner et al. 1986; Josepshon 1993; Toji et al. 1997; Newton et al. 1997). The majority of the studies have used untrained subjects and have reported the maximal dynamic mechanical power as a percentage of maximal isometric force production with no estimates of muscle power and velocity with regard to the actual dynamic exercises used in strength and conditioning programmes (e.g. squat or bench press) or the athletic performance itself.

Previous studies have examined the relationship between maximal power output and load in isolated bundles of muscle fibres (Hill 1938) or in explosive

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movements involving upper or lower body muscle groups such as vertical jumping (Bosco and Komi 1980) or bench-press throws (Newton et al. 1997). However, there is a paucity of data on maximal strength and power of upper and lower extremities muscles in sports activities requiring different levels of strength and power, such as handball, road cycling, middle distance running and Olympic weightlifting. It is likely that the load-velocity and load-power relationships may vary between the different muscle groups, for example, in relation to fibre type distribution, different usage in sport-specific activities and/or biomechanical characteristics of the open and close upper/lower kinetic chains. Classically, strength training programmes have been prescribed according to a percentage of the individual maximal strength (i.e. 1RM). However, velocity-specific increases have been shown with strength training programmes using different speeds of movement (Behm and Sale 1993). Therefore, it would be of interest to determine force/velocity and power/velocity relationships so that athletes perform training exercises at specific load and/or velocity that would be more similar to the conditions of muscle performance required in the actual competitive movement (Wilson et al. 1993; Rahmani et al. 2001). It was hypothesized that the sport-specific time for force application and the sport-specific levels of load to be overcome during strength training should be related to the sport-related differences in maximal strength and/or in the load-power relationship. Therefore, it was of scientific and practical interest to examine to what extent an increase in load may influence the power output in the upper and lower extremity muscles in traditional resistance training exercises and whether it may vary between the subject groups from different sport events with a long history of specific training.

Methods

Subjects

A group of 70 men volunteered to participate in the present investigation. According to their athletic background the subjects were divided into five groups: weightlifters (WL, $n=11$), handball players (HP, $n=19$), amateur road cyclists (RC, $n=18$), middle-distance runners (MDR, $n=10$) and age-matched control subjects (C, $n=12$). The control subjects, who were university students, took part in recreational physical activities such as walking, biking, cross-country hiking and to a lesser extent, swimming and soccer. However, none of the subjects had any background in regular strength training or competitive sports of any kind. The subjects in WL, HP, RC and MDR were members of the same teams in their sport event and had been trained by the same coach for at least the last 3 years. This study was performed between February and May, at the end of the competitive season for HP, at the beginning of the competitive season for RC, and during the competitive season for RC and MDR. During the 5 months preceding the beginning of the study the subjects had trained, on average, five times a week and had participated in competitions at national level.

The subjects in the WL group were placed first or second at their highest national level of competition. Their best weightlifting performance in the competition (snatch and clean and jerk) was [mean (SD)] 217 (17) kg and their Sinclair coefficient was 262.5 (30) (Sinclair 1985). None of the athletes in WL reported that they had used anabolic steroids. All HP were members of the same team and played in the Spanish second division. The MDR had participated in 800 m races at the national level with the best times ranging from 1 min:49 s to 1 min:56 s [mean (SD) 1 min: 52 s (2) s]. The amateur road-cyclists belonged to two cycling teams ranked among the best five national amateur teams. They won more than 25 1 day-races and 4 4–6 days races during the following competitive season. At the end of the following competitive season, 7 of 19 road-cyclists became professionals. The measurements made in the laboratory conditions revealed that their average exercise intensity during a maximal multistage discontinuous incremental cycling test was 490 (56) W equivalent to 6.90 (0.4) $\mathrm{W{\cdot}kg^{-1}}$ body mass. In addition the exercise intensities eliciting a blood lactate concentration of 4 $\mathrm{mmol{\cdot}l^{-1}}$ were 388 (42) W or 5.47 (0.3) $\mathrm{W{\cdot}kg^{-1}}$ body mass.

The characteristics of the subject are presented in Table 1. The subjects were informed carefully about the experiment procedures and about the possible risks and benefits of the project, which had been approved by the Institutional Review Committee of the Instituto Navarro de Deporte y Juventud (Navarra, Spain), and carried out according to the Declaration of Helsinki.

Test procedures

The subjects were carefully familiarized with the test procedure of voluntary force production during several submaximal and maximal actions a few days before the measurements. The subject also completed several explosive type actions to become familiar with the action required to move different loads rapidly. In addition, several warm-up muscle actions were recorded prior to the actual maximal and explosive test actions.

Maximal strength and muscle power tests

Maximal strengths of the upper and lower extremity muscles were assessed using one repetition concentric maximum (1RM) half-squat and bench press actions. In the half-squat ($1RM_{HS}$) the shoulders were in contact with a bar and the starting knee angle was 90°. On

Table 1. Mean (SD) physical characteristics of athletes from different sport events

	Age (years)	Height (cm)	Body mass (kg)	Body fat (%)	Training experience (years)
Weightlifters ($n=11$)	22.6 (3)	177.5 (4)	80.6 (10)^{abc}	11.8 (4)^{ab}	7.5 (4)
Handball players (n = 19)	22.4 (4)	186.1 (7)	83.1 (10)^{abc}	10.7 (3)^{ab}	11.5 (3)
Road Cyclists ($n=18$)	20.6 (1)	181 (16)	67 (15)	5.8 (1)^{c}	8 (3)
Middle-distance runners ($n=10$)	23.1 (5)	177.3 (4)	66.4 (4)	6.9 (1)^{c}	9 (4)
Control subjects ($n=12$)	21.4 (1)	177.7 (4)	71.9 (8)	11.6 (4)	

^{a}Significant difference ($P < 0.05$) compared to road cyclists
^{b}Significant difference ($P < 0.05$) compared to middle-distance runners
^{c}Significant difference ($P < 0.05$) compared to control group

command, the subject performed a concentric leg extension (as fast as possible) starting from the flexed position to reach the full extension of 180° against the resistance determined by the weight plates added to both ends of the bar. The trunk was kept as straight as possible. A security belt was used by all subjects. All the tests were performed in a squatting apparatus in which the barbell was attached to both ends, with linear bearings on two vertical bars allowing only vertical movements. Warm-up consisted of a set of five repetitions at loads of 40%–60% of the perceived maximum. Thereafter, four to five separate single attempts were performed until the subject was unable to extend the legs to the required position. The last acceptable extension with the highest possible load was determined as 1RM. In the bilateral concentric bench press ($1RM_{BP}$) the bar was positioned 1 cm above the subject's chest and supported by the bottom stops of the measurement device. The subject was instructed to perform a purely concentric action from the starting position, maintaining the shoulders in a 90° abducted position to ensure consistency of the shoulder and elbow joints throughout the test movement (Newton et al. 1997). No bouncing or arching of the back was allowed. Three to four trials were performed until the subject was unable to reach the full extension position of the arms. The last acceptable extension with the highest possible load was determined as 1RM. The rest between the actions was always 2 min.

The power-load relationships of the leg and arm extensor muscles were also tested in a half-squat and bench-press position using relative loads of 30%, 45%, 60%, 70%, 80% and 100% of 1RM. In this case the subjects were instructed to move the load as fast as possible. Two test actions were recorded and the best reading (with the highest velocity) was taken for further analyses. The time for rest between each trial and set was always 1.5 min.

During the lower and upper extremity test actions, bar displacement, average velocity (metres per second) and mean power (watts) were recorded by linking a rotary encoder to the end part of the bar. The rotary encoder recorded the position and direction of the bar within an accuracy of 0.0002 m. Customized software (JLML I + D, Madrid, Spain) was used to calculate the power output for each repetition of the half-squat and bench-press performed throughout the whole range of motion. Average power output for each repetition of the half-squat and bench press was determined. Power curves were plotted using average power over the whole range of movement as the most representative mechanical parameter associated with a contraction cycle of each muscle group. Average velocity and power were calculated throughout the whole the range of motion used to perform a complete repetition. For comparison purposes an averaged index of muscle power output with all absolute loads examined was calculated in each group separately. Averaged indexes of muscle power were calculated as the average of the power values obtained under all experimental conditions for a given muscle group.

The reproducibility of the measurements of maximal strength and muscle power output was assessed in two trials separated by 7 days in 11 weightlifters as subjects in a pilot study. Table 2 shows the intraclass correlation coefficients (ICC), Pearson product-moment coefficient (*r*) and coefficient of variation (CV) between the trials for the average power outputs with loads ranging from 30% to 80% of 1RM during the half-squat and bench press actions. No significant differences were observed between the two sets of measurements. The intertest ICC ranged from 0.65 to 0.95, the CV between 4.7% and 7.9% and *r* from 0.57 to 0.98, respectively.

In all these tests of the neuromuscular performance strong verbal encouragement was given to all subjects to motivate them to perform each test action as maximally and as rapidly as possible. The percentage of fat in the body was estimated from measurements of skinfold thickness (Jackson and Pollock 1977).

Statistical methods

Standard statistical methods were used to calculate the means and standard deviations (SD). The average power and velocity results were compared using one-way analyses of variance (ANOVA), and Scheffé post-hoc comparisons to determine differences within loads. Statistical power calculations for this study ranged from 0.75 to 0.80. The $P \leqslant 0.05$ criterion was used for establishing statistical significance.

Results

Physical characteristics

The physical characteristics of the subjects are presented in Table 1. The WL and HP groups showed significantly higher body masses than RC, MDR and C. Percentage body fats were significantly lower in RC and MDR than in the other groups. No significant differences in percentages of body fat were observed between RC and MDR, or between WL, HP and C.

Maximal strength

Table 3 shows the results of the maximal bilateral concentric $1RM_{HS}$ expressed in absolute terms and relative to body mass. Maximal strengths in WL, HP and RC were greater ($P < 0.001$–0.01) than those recorded for MDR and C (Fig. 1 A). Maximal strength in WL was

Table 2. Mean (SD) intraclass correlation coefficients (*ICC*), coefficient of variation (*CV*), and Pearson product-moment coefficient (*r*) between trials for the average power output (*W*) at loads ranging from 30% ($W_{HS30\%}$, $W_{BP30\%}$) to 80% ($W_{HS80\%}$, $W_{BP80\%}$)of one repetition maximum (1RM) half-squat ($1RM_{HS}$) and bench-press ($1RM_{BP}$)

Variable	Day 1	Day 2	ICC Retest	CV (%)	*r*
$1RM_{HS}$	154 (22)	155 (21)	0.90	1.1	0.97***
$W_{HS30\%}$	688 (193)	660 (260)	0.89	6.8	0.81**
$W_{HS45\%}$	816 (205)	905 (192)	0.75	6.9	0.60*
$W_{HS60\%}$	840 (190)	882 (221)	0.93	5.4	0.87***
$W_{HS70\%}$	765 (155)	830 (212)	0.80	6.1	0.70*
$W_{HS80\%}$	667 (123)	661 (196)	0.65	5.2	0.57
$1RM_{BP}$	86 (15)	85 (13)	0.99	0.9	0.98***
$W_{BP30\%}$	442 (115)	467 (113)	0.93	7.9	0.87***
$W_{BP45\%}$	420 (45)	467 (114)	0.97	4.7	0.93***
$W_{BP60\%}$	386 (112)	409 (96)	0.95	7.2	0.91***
$W_{BP70\%}$	348 (108)	382 (85)	0.97	7.3	0.98***
$W_{BP80\%}$	295 (112)	365 (227)	0.95	7.4	0.82**

*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$

Table 3. Mean (SD) maximal bilateral concentric 1RM bench press (*1RM*$_{BP}$) and 1RM half-squat (*1RM*$_{HS}$)in absolute terms and relative to body mass. Definitions are as in Fig. 1

	WL	HP	RC	MDR	C
$1RM_{HS}$ (N)	1,540.2 (176)^{abcd}	1,334.0 (157)^{cd}	1,314.5 (176)^{cd}	1,069.0 (108)	1,030.0 (49)
$1RM_{HS}{\cdot}BM^{-1}$ ($N{\cdot}kg^{-1}$)	19.23 (0.77)^{acd}	16.28 (1.26)^{bd}	18.54 (2.75)^{cd}	16.09 (1.37)^{d}	14.52 (1.37)
$1RM_{BP}$ (N)	873.1 (137)^{abcd}	765.2 (127)^{bcd}	539.5 (69)	539.5 (69)	539.5 (72)
$1RM_{BP}{\cdot}BM^{-1}$ ($N{\cdot}kg^{-1}$)	10.8 (0.98)^{abcd}	9.22 (1.08)^{bcd}	7.55 (0.98)	8.24 (0.88)	7.46 (0.98)

[a] Significant difference ($P < 0.05$) compared to handball players
[b] Significant difference ($P < 0.05$) compared to road cyclists
[c] Significant difference ($P < 0.05$) compared to middle-distance runners
[d] Significant difference ($P < 0.05$) compared to control group

also greater ($P < 0.01$) than those recorded for HP and RC, while no significant differences were observed between HP and RC. When the $1RM_{HS}$ was expressed relative to body mass the difference between WL and RC disappeared, but remained significant between WL and C. The maximal bilateral concentric $1RM_{BP}$ differed between the groups so that the mean value in WL was greater ($P < 0.05$) than that recorded in HP and greater than those recorded for RC, MDR and C (Fig. 1B).

Muscle power output

In the half-squat performance average power outputs at all loads examined (from 30% to 100%) in WL and HP were significantly higher ($P < 0.05$–0.001) than those in MDR, RC and C (Fig. 2 A). The average muscle power outputs in WL at loads of 45% and 60% were significantly higher ($P < 0.001$) than that produced in HP. The only difference observed in the power-load curve between RC, MDR, and C was that average power output at 30% of 1RM in RC was significantly higher ($P < 0.05$) than those recorded in MDR and C.

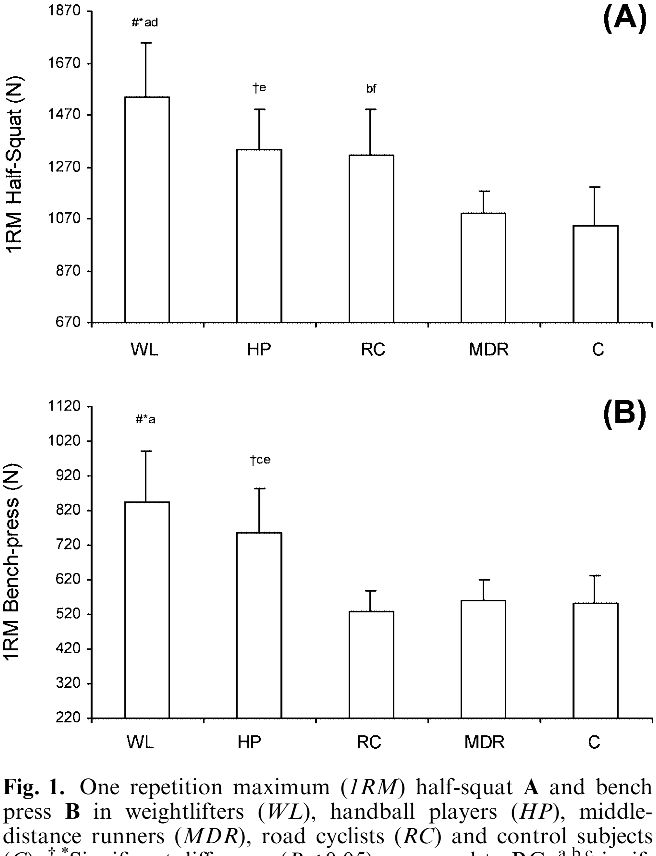

Fig. 1. One repetition maximum (*1RM*) half-squat **A** and bench press **B** in weightlifters (*WL*), handball players (*HP*), middle-distance runners (*MDR*), road cyclists (*RC*) and control subjects (*C*). †,*Significant difference ($P < 0.05$) compared to RC, ^{a,b,c}significant difference ($P < 0.05$) compared to MDR, ^{d,e,f}significant difference ($P < 0.05$) compared to C group, $^{\#}$significant difference ($P < 0.05$) compared to HP. Values are means and SD

Table 4 shows the averaged index of muscle power in absolute terms and relative to body mass. Averaged power output index in absolute and relative to body mass in WL was higher than that in HP and higher ($P < 0.05$) than those in RC, MDR and C.

In the bench-press performance average concentric muscle power outputs at all loads examined in WL and HP were higher ($P < 0.05$–0.001) than those in MDR (n.s. at 80% with HP), RC and C (n.s. at 80% with HP) (Fig. 2B). Average power outputs at 80% and 100% in RC were significantly lower than those recorded in MDR and C. Averaged power output indexes in WL and HP were higher ($P < 0.05$) than those in RC, MDR and C (Table 4). No significant difference in averaged muscle power output index was found between WL and HP.

The shapes of the average bilateral concentric half-squat and bench press power-load curves in absolute values differed between the groups. Maximal power output of the lower extremities was produced at a load of 60% of 1RM [752 (195), 473 (60) and 453 (100) W] for HP, MDR and C, respectively, and at a load of 45% of 1RM [937 (153) and 498 (110) W] for WL and RC (Fig. 2A). In the upper extremity performance, the highest average power output was reached at a load of 30% of 1RM [486 (100) and 468 (76) W] for WL and HP, and at a load of 45% of 1RM [272 (52), 269 (45) and 266 (30) W] for C, MDR and RC, respectively (Fig. 2B).

The power-velocity relationship normalized to body mass during the half-squat and bench-press exercises performed with various loads (from 30% to 100% of 1RM) by all groups are shown in Fig. 3. In the lower extremities, the velocities which elicited the maximal power output in WL and HP [1.06 (0.09) $m{\cdot}s^{-1}$ and 0.96 (0.08) $m{\cdot}s^{-1}$, respectively] were significantly higher ($P < 0.05$) than those recorded for RC, MDR and C [0.75 (0.08), 0.72 (0.09) and 0.70 (0.07) $m{\cdot}s^{-1}$, respectively] (Fig. 3A). In the upper extremities, the velocity that elicited the maximal power output in HP

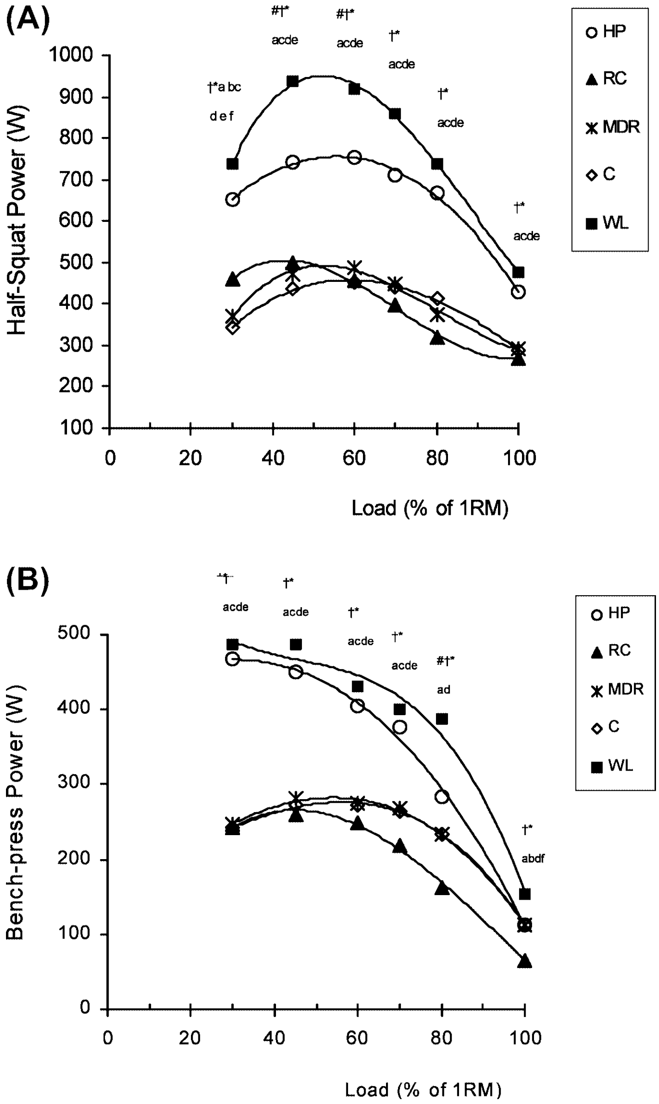

Fig. 2. Average power-load curves in the concentric half-squat **A** and bench-press **B** actions in weightlifters (*WL*), handball players (*HP*), middle-distance runners (*MDR*), road cyclists (*RC*) and control subjects (*C*). Significances as described in Fig. 1

[1.34 (0.11) m·s^{-1}] was significantly higher ($P < 0.05$) than those recorded in WL, MDR, RC and C [0.99 (0.07) m·s^{-1}, 0.92 (0.08), 0.98 (0.08), and 0.80 (0.07) m·s^{-1}, respectively] (Fig. 3B).

Discussion

The present results showed that both absolute maximal strength and muscle power output in the half squat and bench press performance in WL were higher than in HP, which also showed higher values than those recorded in RC, MDR and C. These different levels in maximal strength and power performances observed between the groups could be attributed to the long-term training adaptations and/or to differences in muscle fibre composition. Thus, especially WL but also HP usually perform heavy-resistance training programmes, whereas RC, MDR and C perform low-resistance training or do not perform any strength type of training. The heavy-resistance strength training performed over the years, by especially WL but also HP, may have produced long-term training-induced increases in the maximal voluntary neural drive to the muscles associated with increased rapid neural activation of motor units and/or selective hypertrophy or transformation of type II muscle fibres into stronger counterparts (Häkkinen et al. 1985, 1986; Goldspink 1992; Moritani 1993; Kyrölainen and Komi 1994). Some further plausible explanations for the differences observed in maximal strength and power could be related to muscle fibre composition. It has been demonstrated in earlier studies that athletes specialized in endurance events have a high percentage of slow twitch fibres, while strength/power athletes have been shown to possess a predominance of fast twitch fibres (FT) compared to untrained subjects (Costill et al. 1976; Saltin et al. 1977). Therefore, it is also likely that the obvious differences in muscle fibre distribution between the groups could have contributed in part to the differences in maximal strength and muscle power output performances.

Some differences were observed in the upper and lower body patterns of long-term training adaptation in muscle power between HP and WL. Thus, maximal strength and muscle power output in the lower extremities and maximal strength in the upper extremities were higher in WL than in HP, whereas no significant differences were observed between WL and HP in the ability of the upper extremity muscles to develop maximal power output. The smaller differences observed in WL and HP in muscle power output of the arms compared with the legs may be explained by the low contribution of the arms to the mechanical power development during the Olympic lifts. Thus, in contrast to the legs, it has been shown that during the Olympic lifts the arms act only as cables during the pulls, and as support columns to hold the barbell overhead after the completion of the pulling movement in the snatch or jerk drive in the clean and jerk (Garhammer 1980). In contrast, handball training sessions and competitive games are composed of frequent strenuous activities of the upper muscles such as repetitions of various throws and pushes. Therefore, the smaller differences observed in muscle power output in the arms between WL and HP may be partly related to the difference in the amount and type of activities of the upper extremity muscles used in handball compared to weightlifting training, respectively.

To our knowledge this is the first study that has measured maximal strength and power values in high-level amateur road cyclists. It was interesting to observe that maximal strength values in the lower extremity of RC were higher than in MDR and C and that they were similar when expressed relative to body mass than in WL. Some studies have found similar maximal strength and force-velocity values between middle-distance

Table 4. Mean (SD) average index of muscle power in absolute terms and relative to body mass ($1RM_{HS}·BM^{-1}$). *W* Averaged index of muscle power. Definitions are as in Fig. 1 and other tables

	WL	HP	RC	MDR	C
W_{HS}(W)	755.0 (140)^{abcd}	652.0 (154)^{bcd}	397.0 (99)	394.0 (60)	385.0 (86)
$W_{HS}·BM^{-1}$ (W·kg^{-1})	9.43 (1.7)^{abcd}	8 (2.1)^{bcd}	5.6 (1.3)	5.9 (0.73)	5.5 (0.79)
W_{BP} (W)	391.0 (85)^{bcd}	348.0 (67)^{bcd}	200.0 (38)	225.0 (35)	224.0 (47)
W_{BP} (W·kg^{-1})	4.86 (0.91)^{bcd}	4.22 (0.78)^{bcd}	2.82 (0.48)	3.36 (0.42)	3.24 (0.43)

[a] Significant difference ($P < 0.05$) compared to handball players
[b] Significant difference ($P < 0.05$) compared to road cyclists
[c] Significant difference ($P < 0.05$) compared to middle-distance runners
[d] Significant difference ($P < 0.05$) compared to control group

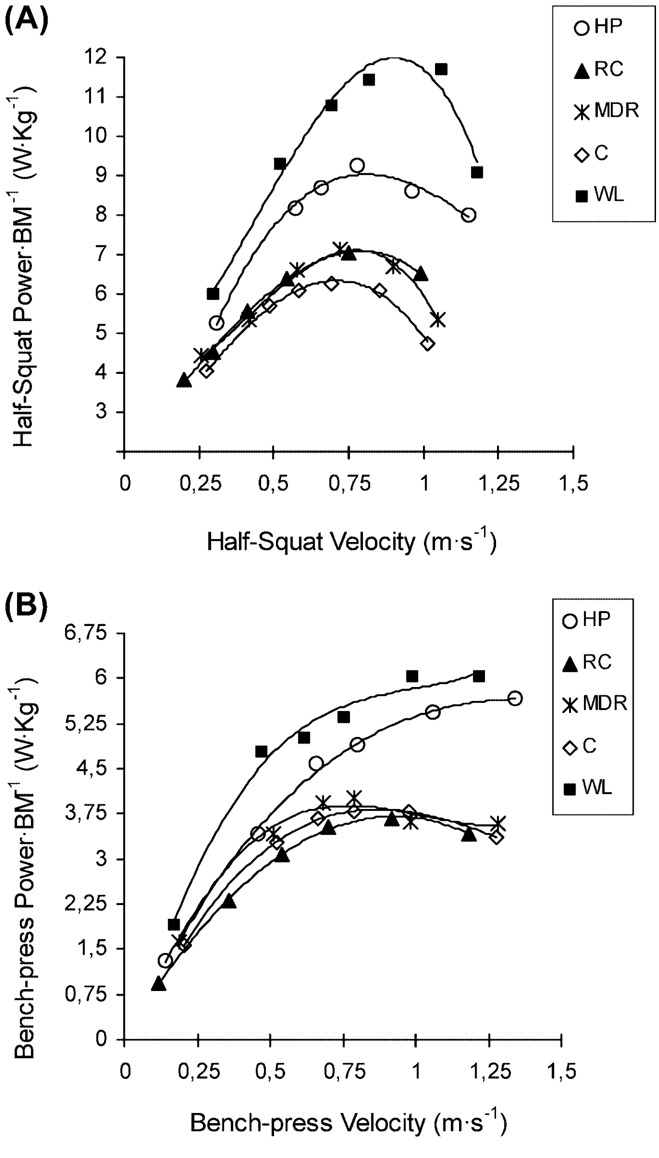

Fig. 3. Average power- velocity curves in the concentric half-squat **A** and bench-press **B** actions in weightlifters (*WL*), handball players (*HP*), middle-distance runners (*MDR*), road cyclists (*RC*) and control subjects (*C*)

runners and age-matched untrained subjects (Kanehisa et al. 1997; Sleivert et al. 1995). The low strength values observed in MDR compared to RC can be explained by the fact that a high percentage of the total volume of training in MDR consists of low-intensity long-duration aerobic training, which involves predominantly a recruitment of low-force-generating capacity slow-twitch fibers (Costill et al. 1976). The high values of maximal strength observed in elite road cyclists was a surprising finding, because the total amount of aerobic training and competitions (12–21 h a week) was higher than in MDR (6–9 h a week), and it has been suggested that a large percentage of low-force-generating capacity slow-twitch fibres is a necessary prerequisite for success in elite cyclists (Coyle et al. 1991). A more likely explanation for the higher maximal strength values observed in RC could have been related to differences in fibre-type recruitment during training and competing in road cycling compared to middle-distance running (Hickson et al. 1988). Thus, it has been reported that during submaximal continuous-exercise cycling at the average relative intensities used by elite cyclists during training and competitions (150–300 W; 60%–70% of maximal oxygen uptake) (Lucía et al. 2001), the peak tension that can be developed with each pedal thrust amounts to 50%–60% of the maximal force which can be exerted on the pedals (Anderson and Sjogaard 1976). This implies an asynchronous activation of motor units with a significant recruitment of FT fibres (Gollnick et al. 1974). However, during submaximal running exercise the peak vertical force represents only 20%–30% of the peak force developed during a maximal vertical jump (Cavanagh and LaFortune 1980). This suggests a predominant recruitment of slow-twitch fibres during each step (Gollnick et al. 1974). In addition, although average relative intensities used by cyclists are near 150–300 W, power output during road cycling is very variable and short bursts of extremely high instantaneous power outputs of 800–1,000 W are interspersed between longer periods of cycling at submaximal intensities (Jeukendrup et al. 2000). Thus, the peak tension developed with each pedal thrust during the short bursts of high power output (more than 60% of the maximal force which can be exerted on the pedals) also exceeds the peak vertical force values reached during sprint running (45% of the peak force developed during a maximal vertical jump) (Cavanagh and LaFortune 1980). The data of the present study also showed that highly trained amateur road cyclists generated almost the same levels of maximal strength relative to body mass as WL. However, this may partly be explained by the fact that WL usually have more muscle mass in the upper body than RC, making this type of comparison somewhat unjustified.

Nevertheless, it is possible that long-term training adaptation due to road cycling is characterized by improved neural activation and intrinsic muscle qualities of the lower extremity muscles.

An interesting finding was that in RC muscle power output production at a load of 30% was significantly greater than those recorded in MDR and C. A plausible explanation of this training-specific adaptation could be related to the similar average times of force application during the concentric actions (for example, at a load of 30% of $1RM_{HS}$ it was 560 ms) and the downstroke portion of the pedal stroke at the pedalling rates preferred by the cyclists (90 rpm) (Coyle et al. 1991). Therefore, it seems that the capacity to generate high muscle power during submaximal dynamic leg extension actions appears to be a significant neuromuscular characteristic of highly trained road cyclists.

To the best of the authors' knowledge only a few studies have examined muscle power output at different loads during the high-intensity short-duration concentric exercises used in strength and conditioning programmes (e.g. squat or bench press) in both upper and lower extremity muscles in athletes from different sports events. Maximal power output has been defined to occur approximately at a force level of 30%–45% of 1RM (Kaneko et al. 1983; Mastropaolo 1992; Moritani 1993; Faulkner et al. 1986; Josepshon 1993; Toji et al. 1997; Newton et al. 1997). In the present study, maximal power output was maximized at a 30%–45% load for the upper, but at a 45%–60% load for the lower extremity extensors depending on the sport group tested. In addition, the velocities that elicited maximal power in the lower extremities were lower ($\approx 0.75\ \text{m}\cdot\text{s}^{-1}$) than in the upper extremities ($\approx 1\ \text{m}\cdot\text{s}^{-1}$) (Fig. 3). It is not known why the velocity and the percentage of 1RM that elicits maximal power are different between the upper and lower extremity actions. Such findings are not uncommon since similar results have also been reported during traditional lifts (e.g. bench-press or squat) in young (Cronin et al. 2000; Rahmani et al. 2001; Bosco et al. 1995), middle-aged and older men (Izquierdo et al. 1999). A possible explanation for these differences observed between the upper and lower extremities may be associated with the extremity-related differences in maximal strength, type of training, muscle cross-section area, fibre-type distribution (Lexell et al. 1983), muscle mechanics (i.e. length and muscle pennation angle) as well as functional differences according to the joint position and geometry of the joints and levers (Gülch 1994). This type of information on different muscle groups and various actions may also be useful to create optimal strength and/or power training programmes for sports with different levels of strength and power demands.

In summary, the results of this study indicated that both absolute maximal strength and muscle power output in the half squat and bench press performance in WL were higher than in HP, which also showed higher values than those recorded in the other athletes examined with different training backgrounds. However, in RC maximal strengths in the half squat and muscle power output production at a load of 30% of 1RM were significantly greater than those recorded in MDR and C. In contrast to the muscle power output of the lower body, no significant differences were observed between WL and HP in the ability of the upper extremity muscles to develop maximal power output. Maximal power output was maximized at a 30%–45% load for the upper extremity extensors and at a 45%–60% load for the lower depending on the sport group tested. In addition, the velocities that elicited the maximal power in the lower extremities were lower ($\approx 0.75\ \text{m}\cdot\text{s}^{-1}$) than in the upper extremities ($\approx 1\ \text{m}\cdot\text{s}^{-1}$). The data suggest that the magnitude of the sport-related differences in strength and/or power may be explained in part by differences in muscle cross-sectional area, fibre type distribution and in muscle mechanics of the upper and lower limbs as well as by training background. This type of information on different muscle groups and various actions may also be useful for creating optimal strength and/or power training programmes for sports with different levels of demand for strength and power.

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