ORIGINAL ARTICLE

Optimum loading for maximizing muscle power output: the effect of training history

Nemanja Pazin · Predrag Bozic · Berjan Bobana · Aleksandar Nedeljkovic · Slobodan Jaric

Abstract Although the effect of external load on the mechanical output of individual muscle has been well documented, the literature still provides conflicting evidence regarding whether the optimum loading (L_{opt}) for exerting the maximum muscle power output (MPO) could be different for individuals with different levels of strength and power. The aim of this study was to explore the effect of training history on L_{opt} that maximizes MPO during the 6-s maximal cycling sprint test. Forty healthy young males (strength-and speed-trained athletes, and physically active and sedentary non-athletes) were tested on maximum strength, and on peak MPO when loaded 5–12% of body weight (BW). As expected, the strength trained and sedentary participants, respectively, revealed the highest and lowest strengths and MPO ($p < 0.001$). However, the main finding was a significant across-group difference in L_{opt} ($p < 0.001$) revealing the values 9.7% (for strength trained), 9.2% (speed trained), 8.7% (active), and 8.0% of BW (sedentary individuals). This suggests that the effects of external loading on maximum MPO in complex functional movements could be training history dependent. In addition to revealing a sensitivity of the 6-s maximal cycling sprint tests (and, perhaps, other maximum cycling tests), the results suggest that the external loading in routine MPO tests should not be solely adjusted to a fixed percentage of subject's BW (as routinely done in standard tests), but also to their training history. The same phenomenon remains to be evaluated in a number of other routine tests of MPO and other maximum performance tasks.

Keywords Maximum cycling · Test · Strength · Fitness

Introduction

Physical performance tests have been widely used to assess muscle function, provide normative values for various groups of subjects, evaluate the effectiveness of training and rehabilitation procedures, prevent injuries, and evaluate the performance capabilities for sport- and work-related activities (Astrand and Rodahl 1986; Jaric 2002; Wilson and Murphy 1996). Relative simplicity, high reliability, and on average moderate validity have vastly contributed to the popularity of the physical performance tests in areas such as sports medicine, athletics, physical education, physical medicine and rehabilitation, and ergonomics. Among the most often assessed physical abilities has been the capacity for exerting high muscle power output (MPO) which has been believed to be particularly important for performing rapid movements against moderate loads (Cronin and Sleivert 2005; Newton and Kraemer 1994). These assessments have been based on recording either the externally exerted muscle force and movement velocity, or work done during complex movements such as cycling (e.g., Wingate test), running (e.g., Margaria staircase test), and jumping (e.g., Sargent jump), or from single joint movements controlled by an isokinetic apparatus (for

N. Pazin · P. Bozic · B. Bobana · A. Nedeljkovic
Faculty of Sports and Physical Education, The Research Center, University of Belgrade, Belgrade, Serbia

P. Bozic · B. Bobana
Serbian Institute of Sport, Belgrade, Serbia

S. Jaric (✉)
Department of Kinesiology and Applied Physiology, University of Delaware, Rust Arena, Rm. 143, 541 South College Avenue, Newark, DE 19716, USA
e-mail: jaric@udel.edu

details see Van Praagh and Dore 2002; Vandewalle et al. 1987).

It has been generally presumed that similar to the mechanical properties of an in vitro muscle (Hill 1938), there is an optimum external loading that allows the musculoskeletal system to maximize MPO in particular movement tasks. For example, the optimum load (L_{opt}) for maximizing MPO could be 0–59% of one repetition maximum (1RM) in vertical jumping (Baker et al. 2001b; Izquierdo et al. 1999; Markovic and Jaric 2007; Nuzzo et al. 2010), 30–70% of 1RM in the bench press (Baker et al. 2001a; Cronin et al. 2001; Newton et al. 1997; Siegel et al. 2002; Thomas et al. 1996), 60–68% of 1RM in the leg press (Lund et al. 2004; Macaluso and De Vito 2003; Thomas et al. 2007), or 30–40% of body weight (BW) in the Margaria test (Caiozzo and Kyle 1980; Kitagawa et al. 1980), while in the cycling tasks (such as Wingate test) L_{opt} could be within 5–10% of BW (Dore et al. 2000; Dore et al. 2003; Dotan and Bar-Or 1983; Evans and Quinney 1981; Patton et al. 1985). The relatively wide intervals of these ranges observed both within and between various tasks could primarily originate from the differences in the data-collection techniques used (Hori et al. 2007), type and position of the external loads applied (Cronin and Sleivert 2005; Jaric and Markovic 2009; Markovic and Jaric 2007), selected variables (e.g., peak or mean power; Cronin and Sleivert 2005), and particularly from the task specificity (Cronin and Sleivert 2005; Kawamori and Haff 2004; Vandewalle et al. 1987). Namely, note that although the outcome of all above cited tests generally reflect muscular power output, the conditions for exerting it vary considerably among them regarding a number of mechanical, anatomical, and neurophysiological factors (McMahon 1984). Finally, the problem of the L_{opt} is not only a theoretical one since the same loading could provide the maximum increase in muscle power when applied in various athletic training and rehabilitation interventions (Cronin and Sleivert 2005; Kawamori and Haff 2004).

In addition to the above-discussed factors that could affect L_{opt} for producing the maximum MPO, there is some evidence that L_{opt} could also be subject specific due to the factors such as age, gender, or training history. For example, younger subjects reveal a higher L_{opt} (relative to the maximum load) than elderly individuals when performing a maximum effort bench press (Izquierdo et al. 1999). The same applies both to males versus females (Dotan and Bar-Or 1983) and to the physically active versus sedentary adults when performing Wingate leg test (Ayalon and Inbar 1974; Evans and Quinney 1981; Patton et al. 1985). Finally, de Vos et al. (2008) found that explosive-resistance training in older adults results in the ability to produce higher MPO against heavier loads without the loss of movement velocity.

All the above-cited findings could be partly in line with the classic literature on muscle mechanics since the typical shape of power-velocity curve implies that stronger muscles (e.g., in males vs. females, or in active vs. sedentary individuals) require a higher external load to maximize power (Faulkner et al. 1986; McMahon 1984). However, there is also some evidence suggesting that the L_{opt} for maximizing MPO may not be subject dependent. For example, Macaluso and De Vito (2003) showed a similar load for maximizing MPO in leg press for males and females, while other studies revealed a similar L_{opt} for various populations evaluated on the Wingate leg test (Dore et al. 2000; Dotan and Bar-Or 1983; Linossier et al. 1993). Nuzzo et al. 2010 suggested a 'zero' load for maximizing MPO in vertical jumps for participants of distinctively different training history. This finding is in line with the maximum dynamic output hypothesis suggesting the weight and inertia of an unloaded body allows for maximizing MPO of leg muscles (Jaric and Markovic 2009).

As reviewed above, the possible differences of L_{opt} in various populations could be both of theoretical and practical importance. Therefore, we designed an experiment with the aim to evaluate both the peak value itself and the differences between peak values in subjects with varied training histories. A 6-s maximal cycling sprint test was selected for the assessment of maximum MPO as it is one of the most popular cycle ergometer tests for both the routine testing and exploring the effects of external loading (Van Praagh and Dore 2002; Vandewalle et al. 1987). In addition to the assessment of L_{opt} which could be of importance for routine testing protocols per se, we evaluated two alternative hypotheses. We expected that the physically active and, particularly, strength trained individuals to demonstrate the maximum MPO under higher external loads than the less active and sedentary individuals. Alternatively, based on a part of the above-reviewed evidence, one could also expect L_{opt} (relative to the subjects' BW) to be the training history independent. The findings were expected not only to provide a basis for a methodological improvement and refinement of the standard muscle power tests, but also to reveal important results regarding understanding some basic aspects of both the design and adaptation of the muscular system.

Methods

Participants

We conducted a sample size estimate based on the differences in muscle strength (McBride et al. 1999; Ugrinowitsch et al. 2007), power (Popadic Gacesa et al. 2009;

Ravier et al. 2004), and velocity (Sbriccoli et al. 2010) among similar groups of participants. Based on Cohen's guidelines (Cohen 1988) with power 0.8 and an alpha level 0.05, sample sizes 4–10 appeared to be necessary per group. Therefore, 40 healthy male volunteers were selected to participate in this study. They were allocated into the following four groups according to their training history: Strength (highly strength trained; $n = 10$; age 24.7 ± 4.6 years of age), Speed (elite karate competitors; $n = 10$; 23.5 ± 3.9), Active ($n = 10$; 22.0 ± 1.4), and Sedentary group ($n = 10$; 24.8 ± 2.7). The subjects' characteristics are depicted in Table 1.

The participants of both the Strength and Speed group were selected on the basis of their sport experience (minimum 3 years), current physical activity (minimum three training sessions a week), and athletic proficiency. The sample of bodybuilders exclusively consisted of medalists on either international or national championships. They should qualify to be 'highly strength trained' due to their weekly training protocol prior to the testing session. Specifically, it involved 3–4 sessions aimed to hypertrophy (i.e., 60–80% 1RM) and 2–3 sessions aimed towards strength (85–100% 1RM). Regarding the Speed group, five karate competitors were members of the national team that became the world champions in the same year when the testing was conducted, while the remaining five were national champions. Note that elite karate competitors demonstrate outstandingly higher speed of leg movements than the amateurs (Sbriccoli et al. 2010). The Active group involved sport and physical education students who were active only through their standard academic curriculum that included 6–8 activity classes per week that involved both low and high intensity exercises. However, none of these subjects have had experience with a regular resistance training. The Sedentary group consisted of low-to-moderately active individuals with no current or prior experience with any kind of athletic training. Their life style activity was assessed by a standard questionnaire (Taylor-Piliae et al. 2006), where six of the participants

reported light and four moderate levels of physical activity. None of the participants reported any medical problems or recent injuries that could compromise the tested performance. Some participants reported taking vitamins, minerals, and other related natural supplements. One participant from the Strength-trained group reported previous use of growth hormone, while the other reported taking weight loss (Clenbuterol) and anabolic steroid (Oxandrolon). However, their strength, power, and L_{opt} was outside of the respective ±1 SD intervals and, therefore, neither of the subjects should have been considered as outlier.

The participants were informed regarding the potential risks associated with the applied testing protocol and asked to sign an informed consent document prior to the testing protocol. The study was approved by the Institutional Review Board, and carried out according to the Declaration of Helsinki.

Experimental procedure

The experiment was carried out within two testing sessions. The first one included anthropometric measurements and medical screening, followed by strength testing and familiarization with the power output tests. The second session consisted entirely of testing the maximum muscle power output (MPO).

Testing protocols

Anthropometric measures were taken according to the procedures recommended by the International Society for the Advancement of Kinanthropometry (Norton et al. 2000). Body height and body mass were measured to the nearest 0.5 cm and 0.1 kg, respectively. Body composition (lean body mass and percentage of body fat content) was assessed through the skinfold measurements. They were taken from biceps, triceps, thigh, calf, chest, and abdomen to the nearest 0.2 mm using a skinfold caliper (John Bull,

Table 1 Subjects characteristics (mean ± SD)

Variable	Strength group ($n = 10$)	Speed group ($n = 10$)	Active group ($n = 10$)	Sedentary group ($n = 10$)
Height (m)	1.76 ± 0.04	1.82 ± 0.06	1.82 ± 0.1	1.80 ± 0.08
Body mass (kg)	85.5 ± 7.4	82.5 ± 7.2	79.5 ± 7.2	77.9 ± 7.4
Lean body mass (kg)	81.5 ± 7.3	76.5 ± 4.1	73.1 ± 6.4[a, b]	68.6 ± 6.4[a, b]
Body fat (%)	4.7 ± 0.8	7.3 ± 1.6	8.5 ± 2.7[a, b]	11.9 ± 3.7[a, b, c]
1RM (kg)	206 ± 19.2	163 ± 19.2[a]	131.8 ± 9.1[a, b]	116.0 ± 17.3[a, b]

Significant difference at level $p < 0.05$; 1RM, strength test (one repetition maximum squat test)

[a] Significantly different from Strength group

[b] Significantly different from Speed group

[c] Significantly different from Active group

England) by the same experienced investigator. The skin-folds were measured in triplicate and the average value was taken for further analysis.

Following the anthropometric measurements, a standard procedure (McBride et al. 1999) was applied to assess the leg extensor strength through one repetition of squats (1RM). Prior to the start of the warm-up procedure, a manual goniometer was used to visually demonstrate the attainment of a 90° knee flexion angle while squatting. The applied loading and the number of the associated warm-up trials were as follows: 30% (8 repetitions), 50% (4–6 repetitions), 70% (2–4 repetitions), and 90% (1 repetition) of an estimated 1RM either based on the subjects recommendation or on calculated 1.5–2 times the subject's BW. The test included one to three trials to assess 1RM. Each subject was asked to control lowering of the bar to the level that provided the 90° of knee angle. Following the reaching of the lowest position, they were instructed to immediately move the weight upward in a controlled but forceful fashion back to the starting position. Adequate rest was allowed between trials (3–5 min). Finally, although most of the participants have already had cycling experience, a familiarization with the test of maximum MPO was conducted. The total of 16 trials performed under various loads was conducted in a random sequence.

The second session consisted entirely of testing the maximum MPO through the 6-s maximal cycling sprint test (Logan et al. 2000; Mendez-Villanueva et al. 2007) performed on a Monark 834E leg cycle ergometer (Monark, Varberg, Sweden). This test represents a short version of the standard Wingate anaerobic test recommended for providing a "more accurate determination of absolute power than the longer Wingate test, as this emphasizes alactic energy derivation only" (c.f., Logan et al. 2000; pp 220). Several studies confirmed high test–retest reliability of this ($r = 0.98$; Wilson et al. 1993) and similar sprint cycling tests ($r = 0.89$–0.96; (Dotan and Bar-Or 1983; Evans and Quinney 1981; Patton et al. 1985), while Mendez-Villanueva et al. (2007) found low within-subject variations when the 6-s maximal cycling sprint test was preceeded by a familiarization session (CV < 2%). A potential advantage of the selected cycling test could also be that it was non-specific for each group of participants. Finally, when compared with other standard tests of MPO (e.g., Margaria, vertical jumps, isokinetic testing), the selected 6-s maximal cycling sprint test allows a simple and accurate manipulation of external loading. The maximal 6-s cycling sprints were performed with eight different loads within the range 5–12% of BW. Prior to the test, subjects performed a standardized warm-up procedure comprising of 5 min of cycling. A self-selected cadence against 2% of BW frictional load was applied to the fly-wheel, followed by 3 min of easy stretching of the

musculature of lower extremities. Finally, a specific warm-up protocol consisting of two bouts of 3-s maximal acceleration separated by 3-min rest was applied. Following a 5-min recovery period, the subjects performed eight 6-s sprints against different loads in a random sequence. They were instructed to perform an "all out" effort from the very beginning of the test until instructed to stop. The seat height was adjusted to each participant's satisfaction, and toe clips with straps were used to prevent the feet from slipping off the pedals. The start position on the cycle ergometer was strictly standardized: the subject was seated on the saddle during the sprint and initiated the exercise with his preferred leg, the crank located at 45° forward. Strong verbal encouragement was provided during each trial. The rest period among consecutive sprints was 4 min. Fatigue was never an issue.

The subjects were asked to follow their normal diet and to refrain from any form of intense physical activity for the 48 h, as well as to fast for 2 h prior to each testing session.

Data analysis

Descriptive statistics were calculated for all experimental data. The percent body fat was calculated using a previously recommended Matiegka's method (Montagu 1960). The maximum MPO was assessed by the peak MPO, which was calculated from the braking force and velocity (in W) each maximal 6-s cycling bout by the computer software. Although the differences in body mass among the groups were somewhat below the significant level (see "Results"), they were relatively large (e.g., about 10% between the Strength and Sedentary group). Therefore, both indices of power were also normalized for body size using the body mass raised to the power of 0.67 (i.e., in W/kg$^{0.67}$; Jaric 2002) providing the normalized values of peak MPO.

One-way analysis of variance with a Tukey post hoc comparisons test was used for the between-group analyses of the subject characteristics (i.e., age, height, weight, % body fat, lean body mass, and 1RM). The Kolmogorov–Smirnov test was applied to determine the distribution of the absolute and normalized peak MPO for each group and applied loading. Since all sets of data revealed normal distribution ($p > 0.07$), a two-way mixed model ANOVA and Bonferroni post hoc comparisons test were used to evaluate the main effects of 'group' and 'load' on normalized values of peak MPO. Since the post hoc effects of load suggested the maximum values of the dependent variable within the applied loading interval, a second step of analysis was conducted to assess the optimum load (L$_{opt}$) that provides the peak MPO. Specifically, a second-order polynomial (i.e., parabolic) regression was fitted through the individual sets of data (i.e., the absolute values of peak MPO obtained from eight loading conditions) that,

Fig. 1 Differences in the normalized peaks of the muscle power output (normalized peak MPO) obtained under various external loads
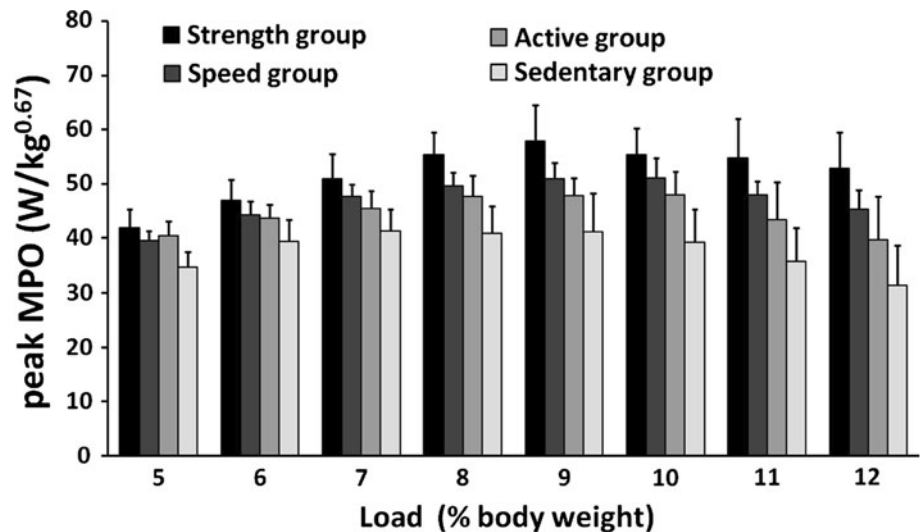
therefore, did not require normalization for body size. Presuming the regression equation:

$$MPO = aL^2 + bL + c, \qquad (1)$$

where L is the applied load and a, b and c parameters, the first derivative allowed for calculation of the L_{opt} corresponding to maximum of the fitted individual curve:

$$L_{opt} = -b/(2a), \qquad (2)$$

while the corresponding correlation coefficient and 95% confidence intervals (95% CI) revealed the strength of the tested load–power relationship. Finally, a one-way model ANOVA with a Tukey post hoc comparisons test was employed to test the differences in the L_{opt} among the groups of participants regarding the peak MPO. A significant level of $p < 0.05$ was used for all comparisons. According to Cohen (1988) the magnitude of difference was tested by means of effect size, where difference was considered either small (0.2), moderate (0.5), or large (0.8). All statistical tests were performed using SPSS 16.0 (SPSS Inc, Chicago, IL) and Office Excel 2003 (Microsoft Corporation, Redmond, WA).

Results

The subject characteristics are summarized in Table 1. One-way ANOVA revealed significant differences in percent body fat ($F_{[3, 36]} = 16.05$, $p < 0.001$) and lean body mass ($F_{[3, 36]} = 7.83$, $p < 0.001$) among the groups, while the differences among other anthropometric variables did not occur. Of particular importance could be the observed differences in the strength of the leg extensor muscles (i.e., 1RM test; $F_{[3,36]} = 45.16$, $p < 0.001$). The post hoc test revealed higher values of 1RM in the Strength and Speed

group than in the remaining non-athletic groups. Also, the Strength group revealed a higher 1RM than the Speed group.

Figure 1 shows the averaged across the subject values of the normalized peak MPO for each particular group and load. In addition to the significant main effect of group ($F_{[3, 36]} = 25.8$, $p < 0.001$) and load ($F_{[7, 252]} = 48.35$, $p < 0.001$), a two-way ANOVA also revealed a significant group × load interaction ($F_{[21, 252]} = 5.43$, $p < 0.001$). As illustrated by the data, the post hoc test showed significant differences among all groups, where the Strength and Sedentary group revealed the highest and lowest normalized values of peak MPO, respectively. The tested values were also higher under intermediate loads (i.e., 8–9% of BW) than under the light or heavy loading (e.g., 5–6 or 11–12% of BW).

The individual second-order polynomial regressions were obtained from the absolute values of peak MPO recorded under each of the applied loads (see Fig. 2 for illustration). The corresponding median (range, 95% CI) correlation coefficients were $r = 0.91$ (0.81–0.97, CI = 0.06), $r = 0.91$ (0.88–1.00, CI = 0.06), $r = 0.90$ (0.70–0.97, CI = 0.11), $r = 0.92$ (0.58–0.98, CI = 0.14) for the Strength, Speed, Active, and Sedentary group, respectively. Note that despite a limited number of data points, 38 individual relationships appeared to be significant ($p < 0.05$), and only the remaining 2 were somewhat below the level of significance.

Figure 3 illustrates the main finding of the present study. L_{opt} revealed values [mean (SD)] ranging from 9.66 (0.63) to 7.99 (1.06) % of BW for the Strength and Sedentary group, respectively, while the remaining results revealed intermediate values of 9.22 (0.47) for the Speed and 8.65 (1.04) % of BW for the Active group. One-way ANOVA revealed significant main effects of group ($F_{[3, 36]} = 10.38$,

Fig. 2 Regression curves depicting the relationship between the load and the peak muscle power output (peak MPO) in representative individuals of four groups. The maxima correspond to individual optimum loads (L$_{opt}$)
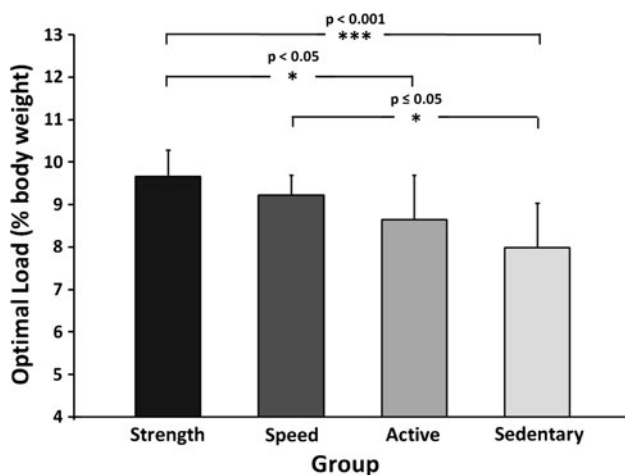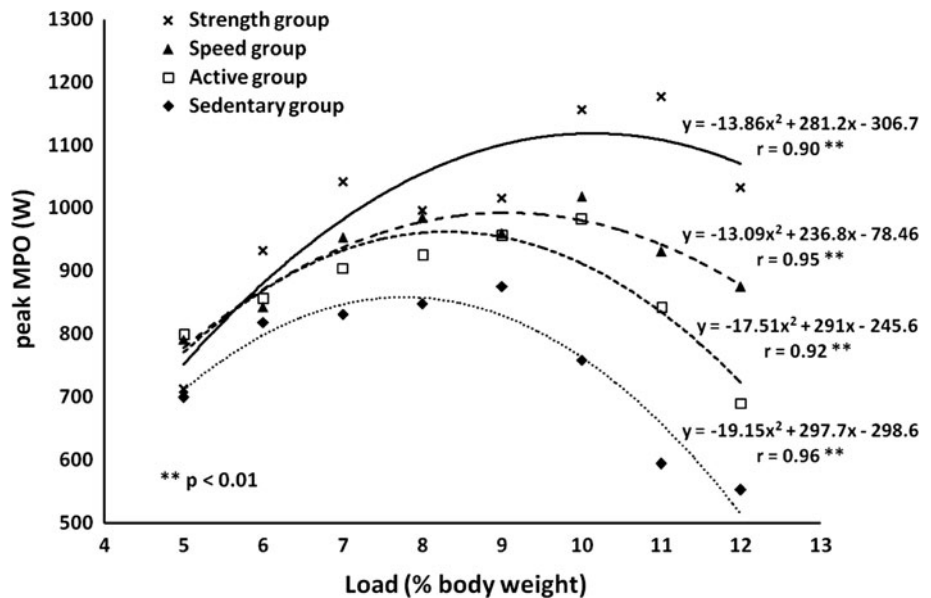
Fig. 3 The optimum load (L$_{opt}$) for producing the peak muscle power output (peak MPO) in four groups of participants

$p < 0.001$), where Tukey post hoc test revealed higher L$_{opt}$ in the Strength than in the Active and Sedentary group (ES = 1.17 and ES = 1.92, respectively), as well as higher in the Speed than in Sedentary group (ES = 1.50).

Discussion

In the present study, we evaluated the effect of an external load on the peak values of the MPO through the 6-s maximal sprint cycling test. In addition to the assessment of the optimum load (L$_{opt}$), we also tested the hypothesized differences among the individuals with distinctively different training histories.

Overall, the obtained absolute values of maximum MPO correspond to the values reported in other studies

performed on similar groups of participants (Popadic Gacesa et al. 2009; Zupan et al. 2009). The recorded range of L$_{opt}$ of 8–10% is generally in line with a number of previous results obtained from both the Wingate and other tests based on all-out cycling tests (Dore et al. 2003; Dotan and Bar-Or 1983; Evans and Quinney 1981; Linossier et al. 1993; Patton et al. 1985), but somewhat higher than others (Ayalon et al. 1974; Dore et al. 2000). Of particular importance could be that both the significant differences and large effect sizes in MPO were observed not only between the groups of athletes and non-athletes, but also between two groups of athletes, while the parabolic MPO-load relationship that revealed L$_{opt}$ proved to be strong and highly significant in most of the participants. While the former finding reveals a high sensitivity of maximum cycling tests when assessing MPO (c.f., Logan et al. 2000; pp 220), the later one suggests importance of an accurate assessment of external loads and, consequently, stresses the significance of the main finding regarding the differences in L$_{opt}$ observed among the tested groups. Therefore, the remaining part of this section will discuss the theoretical and practical implications of the effect of training history on L$_{opt}$.

From the theoretical perspective, of primary interest could be both the properties and the adaptation mechanisms of the neuromuscular system that could play a role in the recorded differences in L$_{opt}$. A relatively simple explanation of the observed phenomenon could be based on the recorded differences in muscle strength and the effect of those differences on the classical force-velocity relationship of individual muscles. Specifically, relatively stronger muscles (such as in individuals of the Strength group) may require a higher external load relative to their BW to reach the speed of shortening that maximizes

muscle power. However, several aspects of both the design and action of the muscular system could also play a role. Regarding the action of individual muscles during cycling, it changes over a wide range of contraction velocities, including both the concentric and eccentric ones. Furthermore, the pattern of muscle activation may be quite different for muscles acting in individual joints, as well as for the single- and multi-joint muscles acting in the same joint (Vandewalle et al. 1987). Therefore, the mechanical properties of individual muscles (such as strength or L_{opt}) may not fully characterize the same properties of the entire leg musculature during complex movements, such as cycling. In addition, the L_{opt} that maximizes MPO in vertical jumping could be the subjects own body (Jaric and Markovic 2009; Markovic and Jaric 2007), even in individuals with distinctive strength capabilities (Nuzzo et al. 2010). Some previous data obtained from the Wingate test also suggest that the L_{opt} in participants of partly different training histories could be similar (Dotan and Bar-Or 1983; Linossier et al. 1993), although BW could still be a strong predictor (Patton et al. 1990). Although none of the above-cited studies were based on the 6-s maximal sprint cycling test, they at least implicitly contradict our main finding. Therefore, further research is needed to explore whether L_{opt} for exerting the maximum MPO is the training history and, particularly, to which extent the training-associated adaptation of muscle strength and power play a role in the observed phenomenon. Finally, particularly longitudinal studies should be needed to reveal whether the differences in L_{opt} could originate from the neuromuscular adaptation to training/rehabilitation procedures or, alternatively, from other sources, such as early selection.

Regarding the practical aspect, the importance of the differences in L_{opt} across the tested groups is augmented by prominent peaks of the power-load relationship. Namely, the later finding suggests the importance of applying an accurate load for the tested outcome. Since the external load has been routinely standardized as a particular percentage of BW in various maximum cycling tests of MPO (Bar-Or 1987; Dore et al. 2000; Vandewalle et al. 1987), our results suggest that they could also be training history dependent. For example, relatively higher loading (relative to BW) should be applied to the individuals of a higher level of physical fitness and, particularly, on those who exercise against high external resistance, than on the sedentary individuals. It remains to be seen whether and to which extent the same applies to the other routine tests of MPO, such as the Margaria test (Margaria et al. 1966), vertical jumps (Markovic and Jaric 2007; Nuzzo et al. 2010), or single joint movements performed on isokinetic devices (Vandewalle et al. 1987).

Conclusion

Although we also found the differences among the individuals with different training history regarding the overall magnitude of MPO, the main findings of this study are the observed differences in L_{opt} (as % of BW) that maximize MPO. Taking into account both the conflicting findings and related theoretical models in the literature regarding L_{opt}, exploration of the same phenomena in other maximum performance movement tasks is needed to reveal important properties of the neuromuscular system and its adaptations related to external loading. From the practical aspect, the results generally suggest that although various maximal cycling sprint tests could be sensitive enough to detect differences among the participants of different levels of fitness, the external loading could also need to be adjusted relative to the subjects' training history rather than solely to the fixed percentage of BW. The same effect remains to be evaluated in a number of other routine tests of MPO and other maximum performance tasks, particularly regarding the relative contribution of BW and training history.

References

Astrand P-O, Rodahl K (1986) Textbook of work physiology. McGraw-Hill, New York

Ayalon A, Inbar O, Bar-Or O (1974) Relationships among measurements of explosive strength and anaerobic power. In: Nelson RC, Morehouse CA (eds) Biomechanics, vol IV. University Park Press, Baltimore, pp 527–532

Baker D, Nance S, Moore M (2001a) The load that maximizes the average mechanical power output during explosive bench press throws in highly trained athletes. J Strength Cond Res 15:20–24

Baker D, Nance S, Moore M (2001b) The load that maximizes the average mechanical power output during jump squats in power-trained athletes. J Strength Cond Res 15:92–97

Bar-Or O (1987) The Wingate anaerobic test. An update on methodology, reliability and validity. Sports Med 4:381–394

Caiozzo VJ, Kyle CR (1980) The effect of external loading upon power output in stair climbing. Eur J Appl Physiol Occup Physiol 44:217–222

Cohen J (1988) Statistical power analysis for the behavioral sciences. Lawrence Erlbaum Associates, Hillsdale

Cronin J, Sleivert G (2005) Challenges in understanding the influence of maximal power training on improving athletic performance. Sports Med 35:213–234

Cronin J, McNair PJ, Marshall RN (2001) Developing explosive power: a comparison of technique and training. J Sci Med Sport 4:59–70

de Vos NJ, Singh NA, Ross DA, Stavrinos TM, Orr R, Fiatarone Singh MA (2008) Effect of power-training intensity on the

contribution of force and velocity to peak power in older adults. J Aging Phys Act 16:393–407

Dore E, Bedu M, Franca NM, Diallo O, Duche P, Van Praagh E (2000) Testing peak cycling performance: effects of braking force during growth. Med Sci Sports Exerc 32:493–498

Dore E, Duche P, Rouffet D, Ratel S, Bedu M, Van Praagh E (2003) Measurement error in short-term power testing in young people. J Sports Sci 21:135–142

Dotan R, Bar-Or O (1983) Load optimization for the Wingate Anaerobic Test. Eur J Appl Physiol Occup Physiol 51:409–417

Evans JA, Quinney HA (1981) Determination of resistance settings for anaerobic power testing. Can J Appl Sport Sci 6:53–56

Faulkner JA, Clafin DR, McCully KK (1986) Power output of fast and slow fibers from human skeletal muscles. In: Jones NL, McCartney N, McComas AJ (eds) Human muscle power. Human Kinetics, Champaign, pp 88–100

Hill AV (1938) The heat of shortening and the dynamic constants of muscle. Proc R Soc Med (Lond) 126:136–195

Hori N, Newton RU, Andrews WA, Kawamori N, McGuigan MR, Nosaka K (2007) Comparison of four different methods to measure power output during the hang power clean and the weighted jump squat. J Strength Cond Res 21:314–320

Izquierdo M, Ibanez J, Gorostiaga E, Garrues M, Zuniga A, Anton A, Larrion JL, Hakkinen K (1999) Maximal strength and power characteristics in isometric and dynamic actions of the upper and lower extremities in middle-aged and older men. Acta Physiol Scand 167:57–68

Jaric S (2002) Muscle strength testing: use of normalisation for body size. Sports Med 32:615–631

Jaric S, Markovic G (2009) Leg muscles design: the maximum dynamic output hypothesis. Med Sci Sports Exerc 41:780–787

Kawamori N, Haff GG (2004) The optimal training load for the development of muscular power. J Strength Cond Res 18:675–684

Kitagawa K, Suzuki M, Miyashita M (1980) Anaerobic power output of young obese men: comparison with non-obese men and the role of excess fat. Eur J Appl Physiol Occup Physiol 43:229–234

Linossier MT, Denis C, Dormois D, Geyssant A, Lacour JR (1993) Ergometric and metabolic adaptation to a 5-s sprint training programme. Eur J Appl Physiol Occup Physiol 67:408–414

Logan P, Fornasiero D, Abernethy P, Lynch K (2000) Protocols for the assessment of isoinertial strength. In: Gore CJ (ed) Physiological tests for elite athletes. Human Kinetics, IL, pp 200–222

Lund RJ, Dolny DG, Browder KD (2004) Optimal loading during two different leg-press movements in female rowers. Med Sci Sports Exerc 36:148–154

Macaluso A, De Vito G (2003) Comparison between young and older women in explosive power output and its determinants during a single leg-press action after optimisation of load. Eur J Appl Physiol 90:458–463

Margaria R, Aghemo P, Rovelli E (1966) Measurement of muscular power (anaerobic) in man. J Appl Physiol 21:1662–1664

Markovic G, Jaric S (2007) Positive and negative loading and mechanical output in maximum vertical jumping. Med Sci Sports Exerc 39:1757–1764

McBride JM, Triplett-McBride T, Davie A, Newton RU (1999) A comparison of strength and power characteristics between power lifter, olympic lifters, and sprinters. J Strength Cond Res 13:58–66

McMahon TA (1984) Muscles, reflexes, and locomotion. Princeton University Press, Princeton

Mendez-Villanueva A, Bishop D, Hamer P (2007) Reproducibility of a 6-s maximal cycling sprint test. J Sci Med Sport 10:323–326

Montagu MFA (1960) A Handbook of anthropometry. Charles C Thomas Publishers, Springfield

Newton RU, Kraemer WJ (1994) Developing explosive muscular power: implications for a mixed methods training strategy. Strength Cond J 16:20–31

Newton RU, Murphy AJ, Humphries BJ, Wilson GJ, Kraemer WJ, Hakkinen K (1997) Influence of load and stretch shortening cycle on the kinematics, kinetics and muscle activation that occurs during explosive upper-body movements. Eur J Appl Physiol Occup Physiol 75:333–342

Norton K, Marfell-Jones M, Whittingham N, Kerr D, Carter L, Saddington K, Gore C (2000) Anthropometric assessment protocols. In: Gore CJ (ed) Physiological tests for elite athletes. Human Kinetics, IL, pp 66–85

Nuzzo JL, Cavill MJ, Triplett NT, McBride JM (2010) A descriptive study of lower-body strength and power in overweight adolescents. Pediatr Exerc Sci 21:34–46

Patton JF, Murphy MM, Frederick FA (1985) Maximal power outputs during the Wingate anaerobic test. Int J Sports Med 6:82–85

Patton JF, Kraemer WJ, Knuttgen HG, Harman EA (1990) Factors in maximal power production and in exercise endurance relative to maximal power. Eur J Appl Physiol Occup Physiol 60:222–227

Popadic Gacesa JZ, Barak OF, Grujic NG (2009) Maximal anaerobic power test in athletes of different sport disciplines. J Strength Cond Res 23:751–755

Ravier G, Grappe F, Rouillon JD (2004) Application of force-velocity cycle ergometer test and vertical jump tests in the functional assessment of karate competitor. J Sports Med Phys Fitness 44:349–355

Sbriccoli P, Camomilla V, Di Mario A, Quinzi F, Figura F, Felici F (2010) Neuromuscular control adaptations in elite athletes: the case of top level karateka. Eur J Appl Physiol 108:1269–1280

Siegel JA, Gilders RM, Staron RS, Hagerman FC (2002) Human muscle power output during upper- and lower-body exercises. J Strength Cond Res 16:173–178

Taylor-Piliae RE, Norton LC, Haskell WL, Mahbouda MH, Fair JM, Iribarren C, Hlatky MA, Go AS, Fortmann SP (2006) Validation of a new brief physical activity survey among men and women aged 60–69 years. Am J Epidemiol 164:598–606

Thomas M, Fiatarone MA, Fielding RA (1996) Leg power in young women: relationship to body composition, strength, and function. Med Sci Sports Exerc 28:1321–1326

Thomas GA, Kraemer WJ, Spiering BA, Volek JS, Anderson JM, Maresh CM (2007) Maximal power at different percentages of one repetition maximum: influence of resistance and gender. J Strength Cond Res 21:336–342

Ugrinowitsch C, Tricoli V, Rodacki AL, Batista M, Ricard MD (2007) Influence of training background on jumping height. J Strength Cond Res 21:848–852

Van Praagh E, Dore E (2002) Short-term muscle power during growth and maturation. Sports Med 32:701–728

Vandewalle H, Peres G, Monod H (1987) Standard anaerobic exercise tests. Sports Med 4:268–289

Wilson GJ, Murphy AJ (1996) The use of isometric tests of muscular function in athletic assessment. Sports Med 22:19–37

Wilson GJ, Newton RU, Murphy AJ, Humphries BJ (1993) The optimal training load for the development of dynamic athletic performance. Med Sci Sports Exerc 25:1279–1286

Zupan MF, Arata AW, Dawson LH, Wile AL, Payn TL, Hannon ME (2009) Wingate anaerobic test peak power and anaerobic capacity classifications for men and women intercollegiate athletes. J Strength Cond Res 23:2598–2604