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ORIGINAL ARTICLE

Strength training improves cycling efficiency in master endurance athletes

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Abstract The purpose of this study was to test the effect of a 3-week strength training program of knee extensor muscles on cycling delta efficiency in master endurance athletes. Nine master (age 51.5 ± 5.5 years) and 8 young (age 25.6 ± 5.9 years) endurance athletes with similar training levels participated in this study. During three consecutive weeks, all the subjects were engaged in a strength training program of the knee extensor muscles. Every week, they performed three training sessions consist of 10 × 10 knee extensions at 70% of maximal repetition with 3 min rest between in a leg extension apparatus. Maximal voluntary contraction torque (MVC torque) and force endurance (End) were assessed before, after every completed week of training, and after the program. Delta efficiency (DE) in cycling was evaluated before and after the training period. Before the training period, MVC torque, End, and DE in cycling were significantly lower in masters than in young. The strength training induced a significant improvement in MVC torque in all the subjects, more pronounced in masters (+17.8% in masters vs. +5.9% in young, $P < 0.05$). DE in cycling also significantly increased after training in masters, whereas it was only a trend in young. A significant correlation ($r = 0.79$, $P < 0.01$) was observed between MVC torque and DE in cycling in masters. The addition of a strength training program for the knee extensor muscles to endurance-only training induced a significant improvement in strength and cycling efficiency in master athletes. This enhancement in muscle performance alleviated all the age-related differences in strength and efficiency.

Keywords Aging · Maximal voluntary contraction · Delta efficiency · Muscle performance · Master athlete

Introduction

In the last decades, the participation of middle-aged and elderly trained people in endurance events has dramatically increased (Jokl et al. 2004; Lepers 2008). These trained people, commonly called "master athletes", try to maintain their performance level despite the aging process. Accordingly, a constant increase of peak endurance performances in master age groups is reported, however, absolute performance inevitably tends to decline over the years independent of locomotion mode (Lepers and Maffiuletti 2011; Lepers et al. 2010; Peiffer et al. 2008; Tanaka and Seals 2008). In their topical review, Tanaka and Seals (2008) suggest that among the factors affecting endurance performance in master athletes, a decline in maximal oxygen consumption is the primary mechanism causing age related reduction in performance by around 10% per decade. However, several other factors could explain the decline in performance, such as a significant reduction in maximal muscle strength and changes in contractile function despite the regular endurance training (Bieuzen et al. 2010; Faulkner et al. 2008; Louis et al. 2009). Since endurance athletes must be able to sustain a high muscular power output for the duration of a race, this reduction in

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muscular performance could affect the performance and especially the locomotion efficiency, specifically the body's effectiveness in using the oxygen to produce energy and to convert it into muscular work (Moseley and Jeukendrup 2001). Locomotion efficiency and endurance performance in cycling and running have been reported to be highly correlated with maximal strength capacity (Storen et al. 2008; Sunde et al. 2010). Thus, in master subjects, an age-related decrease in maximal strength capacity could increase the relative load applied to lower limb muscles in each movement and so forth induce a greater activation of motor neurons and muscle fibers, lowering locomotion efficiency. Moreover, a lower maximal strength capacity could hasten the occurrence of type I muscle fibers fatigue, resulting in the recruitment of additional type II muscle fibers metabolically less efficient (Crow and Kushmerick 1982). The additional recruitment of type II muscle fibers during the exercise could result in increasing O_2 cost of exercise, and this would lower efficiency.

In the literature, locomotion efficiency has been widely studied in young populations to control the performance level after different training protocols, but rarely in master athletes (Allen et al. 1985; Louis et al. 2009). In young subjects, many authors have reported that even small increments in efficiency may lead to major improvements in endurance (Horowitz et al. 1994; Moseley and Jeukendrup 2001) and among the strategies developed to enhance efficiency, strength protocols are classically used (Saunders et al. 2004). When combining strength and endurance training, several studies have reported an improvement in locomotion efficiency. For example, Millet et al. (2002) have reported a 6.9% increase in running economy (RE) after 14 weeks of strength training performed by young triathletes. More recently, Storen et al. (2008) have shown an augmentation of 5% in RE after 8 weeks of strength training in well-trained endurance runners. An increase in maximal strength production, improved muscle fibers recruitment and muscle coordination, and a delay in type I muscle fibers fatigue, are the main hypotheses to explain the improvement in locomotion efficiency following strength training in young athletes (Aagaard et al. 2002; Hakkinen et al. 1998a; Macaluso and De Vito 2004). While the majority of studies have concerned running, very few were performed in cycling (Sunde et al. 2010; Yamamoto et al. 2008). The little data available on cycling indicates a beneficial effect of strength training on cycling efficiency, but results have been derived from either non-cyclists (Hansen et al. 2007), previously untrained subjects (Loveless et al. 2005) or cyclists already using strength training (Jackson et al. 2007). The only relevant study in cycling is a paper from Sunde et al. (2010), who recorded a 4.7% increase in cycling efficiency after 8 weeks of strength training added to the normal endurance training of competitive cyclists. Based on the previous results, the question of a similar improvement as shown in running and in young cyclists (Sunde et al. 2010) could be raised for master athletes in cycling.

In running, it is more common to calculate the economy than the efficiency. Economy refers to the steady-rate oxygen cost of a standard velocity [in J m^{-1} (diPrampero et al. 1986)], while efficiency (in %) is generally used in cycling. Cycling efficiency can be calculated in different ways, either including whole body energy expenditure (i.e., gross efficiency, GE) or limited to the energy expended to produce movement (i.e., delta efficiency, DE). DE is the ratio of the change in accomplished work to the change in expended energy (Coyle et al. 1992). By eliminating the metabolic processes not contributing to work performance, such as the basal metabolic rate or the work of stabilizing muscles, DE is considered the most valid estimate of muscular efficiency (Coyle et al. 1992; Gaesser and Brooks 1975). Moreover, it has been shown that DE in cycling is correlated with the percentage of type I muscular fibers, constituting a relevant indicator of changes in the muscular efficiency. Within this framework, since the master athletes undergo age-related structural modifications such as a shift toward type 1 muscles fibers, DE would be especially relevant to study age-related changes in efficiency (Horowitz et al. 1994; Mogensen et al. 2006).

The aim of this study was, therefore, to test the effect of an intensive strength training program of lower limb muscles on muscle strength and cycling delta efficiency in young and middle-aged trained people. We hypothesized that intensive strength training performed as knee-extensions in addition to endurance training could be an interesting strategy for master athletes to maintain the endurance performance at a similar level than their young counterparts, principally by acting against the age-related decline in strength production and improving locomotion efficiency.

Materials and methods

Population

Seventeen endurance trained athletes (nine masters vs. eight young athletes, Table 1) participated in this study. Particular care was taken in recruiting individuals with similar activity level and body stature. All the individuals selected were regularly trained subjects engaged in long distance activities (i.e., cycling and triathlon competitions) but none had participated in regular strength training within the last year. Subjects had to be free from present or past neuromuscular and metabolic pathologies which could affect measured variables. All the subjects were volunteers

Table 1 Baseline descriptive characteristics of participants

	Masters ($n = 9$)	Young ($n = 8$)
Age (years)	51.5 ± 5.5†	25.6 ± 5.9
Height (m)	1.76 ± 0.05	1.73 ± 0.08
Weight (kg)	68.2 ± 5.2	66.2 ± 8.6
Fat mass (%)	18.2 ± 3.7	17.5 ± 7.01
VO_{2max} (l min^{-1})	3.77 ± 0.57	3.86 ± 0.99
MAP (W)	300.4 ± 32.4	318.7 ± 85.2
P VT1 (W)	186.1 ± 22.6	189.3 ± 48.0
P VT2 (W)	270.0 ± 36.5	271.2 ± 77.5
Hours of training (per week)	7.7 ± 2.3	7.4 ± 3.6
Years of practice	15.5 ± 4.6†	9.0 ± 1.5

Values are expressed as mean ± SD

VO_{2max} (l min^{-1}) maximal oxygen uptake; *MAP* (W) maximal aerobic power; *P VT1* (W) power at first ventilatory threshold; *P VT2* (W) power at second ventilatory threshold

† Significantly different from young ($P < 0.05$)

and were informed about the study protocol, the risks of tests and investigations, and their rights according to the Declaration of Helsinki. Participants gave their informed written consent and the study was approved by the local Ethics Committee before its initiation.

Experimental design

This experiment was conducted to examine the effect of a 3-week strength training program on muscle strength and cycling efficiency in endurance trained young and master athletes. The experimental protocol consisted of four testing/training sessions in the laboratory; preliminary testing and familiarization, pre-testing (Pre), 3 weeks of strength training (weeks 1, 2, and 3), and post-testing (Post). During the first phase, subjects were familiarized with the test scheme and location, and preliminary tests were performed. Muscle performance was assessed before the last training session of every training week. During the second and the fourth sessions, muscle performance and efficiency were analyzed. From their first visit to the lab until the end of the experimentation period, all the participants were asked to maintain their normal endurance training, but didn't take part in the competitions.

Preliminary session

During a preliminary session, 2 weeks before the experiment, the 17 subjects underwent an incremental cycling test at a self-selected cadence on an electromagnetically braked ergocycle (SRM, Schoberer Rad Messtechnik, Jülich, Welldorf, Germany). The handlebars and racing seat of the ergocycle were fully adjustable both vertically and horizontally enabling reproduction of the positions used by subjects on their own bicycles. Moreover, the ergometer was equipped with individual racing pedals and toe clips, allowing subjects to wear their own shoes. This ergometer allowed subjects to maintain a constant power output independent of the selected cadence, by automatically adjusting torque to angular velocity. The test was performed according to the recommendations of the French Sport Medicine Society. It consisted of a warm-up lasting 6 min at 100 W, and an incremental period in which the power output was increased by 30 W every minute until the volitional exhaustion. During this incremental cycling exercise, oxygen uptake (VO_2), minute ventilation (VE), and respiratory exchange ratio (RER) were recorded cycle-to-cycle with a breathing gas analyzer (Oxycon Pro, Erich Jaeger, Hoechberg, Germany). The criteria used for the determination of VO_{2max} were a plateau in VO_2 despite an increase in power output, a RER above 1.1, and a heart rate (HR) above 90% of the predicted maximal HR (Howley et al. 1995). The maximal oxygen uptake (VO_{2max}) was determined as the average of the four highest VO_2 values recorded (3.86 ± 0.99 l min^{-1} for the young vs. 3.77 ± 0.57 l min^{-1} for the master athletes). The first and the second ventilatory thresholds (VT1 and VT2) were determined according to the method described by Wasserman et al. (1973). The maximal aerobic power output (MAP) was the highest power output completed for 1 min (318.7 ± 85.2 W for the young vs. 300.4 ± 32.4 W for the master athletes). After this cycling exercise, subjects were familiarized with the ergometer to evaluate muscle strength and with the knee extension equipment used for the strength training program.

Training protocol

Each subject was engaged in strength training for three consecutive weeks (three training sessions/week). Briefly explained, the exercise protocol consisted of bilateral strength training (bilateral knee extensions). Quadriceps muscle contractions were performed in a commercial knee extension device (Technogym, Gambettola, Italy) in which both the legs worked against a heavy load [70% of one repetition maximum (1RM)] with a range of motion of 100°–30° (0° = full knee extension). A total of 10 sets of 10 knee extensions were conducted during every training session, lasting 31 min in total (~30 s/set with 3 min recovery between sets, see Fig. 1) (Holm et al. 2008).

Assessment of muscle strength

Subjects were familiarized with strength tests on their first visit to the lab, 2 weeks before the strength training period. First, subjects 1RMs were determined according to the

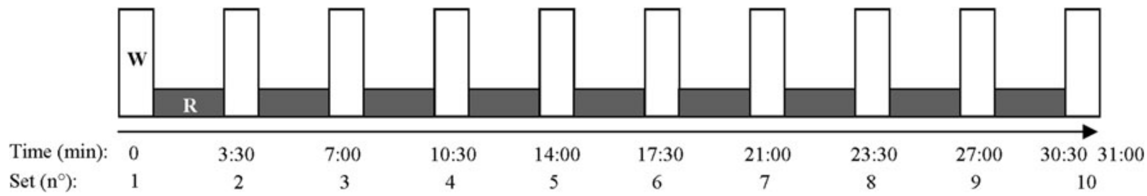

Fig. 1 Strength training protocol design. 10 sets of 10 repetitions of knee extension. *W* muscle work (30 s at 70% of 1 maximal repetition, 1MR), *R* recovery (3 min)

method described by Bishop et al. (1999) using the knee extension equipment described previously. During the 1RM, subjects were allowed to grip the seat with their hands. Following ten submaximal warm-up contractions, subjects were instructed to conduct two bilateral repetitions with loads applied to the lever arm. When a subject was capable of one, but not two knee extensions, the load was noted as 1RM strength.

In the second phase of the experiment (pre-session), the maximal isometric strength of the knee extensors was assessed at 70° knee angle with an isokinetic ergometer (Biodex system 3, Biodex medical, Shirley, NY, USA). In addition, the strength endurance (End test) of extensor muscles was assessed at a knee joint angular velocity of 180°/s and range of motion of 90° to 10° (0° = full knee extension) over 30 consecutive contractions (Pincivero et al. 2003). During the preliminary session, the procedures were thoroughly explained and the subjects were familiarized with the ergometer and the test program. Maximal isometric and endurance strength were assessed during the last training session of each week (week 1, 2, and 3) and 3 days after the final training session (post). After a warm-up which consisted of submaximal isometric contractions, subjects were seated on the ergometer chair with their hips and thigh strapped to the seat. During testing, the arms were folded across the chest, and the strong verbal encouragement was given by the operator. Subjects were instructed to extend their knee "as fast and as hard as possible" and each maximal contraction was sustained for 5 s. Three maximal isometric contractions (MVC) were performed with rest periods of 60 s in between the trials. Subsequently, the strength endurance test (End) was conducted after 5 min of rest. Subjects had to perform 30 consecutive maximal knee extensions/flexions by pushing and pulling the arm of the ergometer as hard as possible (Pincivero et al. 2003).

Before analysis, the force signal was automatically corrected for the effect of gravity on the lower leg. To remove noise from signal, data were smoothed by a 10 Hz third order Butterworth low pass filter, using a custom-written script (Origin Pro 8.1®, OriginLab, Northampton, USA). Maximal voluntary contraction torque (MVC torque) was defined as the highest peak torque value of the three maximal attempts. For the End test, the mean torque produced over the 30 contractions was determined (*T*mean) by averaging the maximal torque value recorded only in the knee extension phase. Muscle endurance was also assessed through the two following methods: the delta torque (last 5 repetitions–5 first repetitions), and a fatigue index (FI). The FI was determined by the following formula to yield a percent decrease (Pincivero et al. 2003): percent decrease = 100 − [(last 5 repetitions/first 5 repetitions) × 100].

Locomotion efficiency

Before and after the strength training protocol (Pre and Post), subjects were asked to perform a cycling control exercise (CTRL) at a freely selected cadence on the same ergocycle as used in the preliminary session. This cycling exercise involved 5 min at 100 W followed by 10 min at an individually adapted heavy power output corresponding to P exercise = 50% of ($P_{VT1} + P_{VT2}$) (Louis et al. 2010). For each subject and each cycling session, metabolic data were continuously recorded to assess the efficiency in cycling. Efficiency can be expressed as a ratio between (external) power output and ensuing energy expenditure (EE). In this study, the delta efficiency (DE) calculation was employed to estimate the muscular efficiency (Coyle et al. 1992; Gaesser and Brooks 1975). DE calculation is based upon a series of work rates which are then subjected to linear regression analysis. In this study, work rates were calculated from the power output developed during warm-up (100 W) and exercise (P mean 228.4 ± 59.7 W for young and 220.6 ± 20.5 W for masters).

$$\text{delta efficiency}(\%) = \frac{\Delta\text{workrate}(\text{WR}, \text{injoules})}{\Delta\text{energy expenditure } (E,\ \text{in joules})} \times 100.$$

In order to obtain precise values for the work rate utilized in the efficiency calculations, power output was assessed from the set work rate and the true cadence as monitored by the SRM crank system. EE was obtained from the rate of oxygen uptake, using the equations developed by Brouwer (1957). These equations take the substrate utilization into account by calculating the

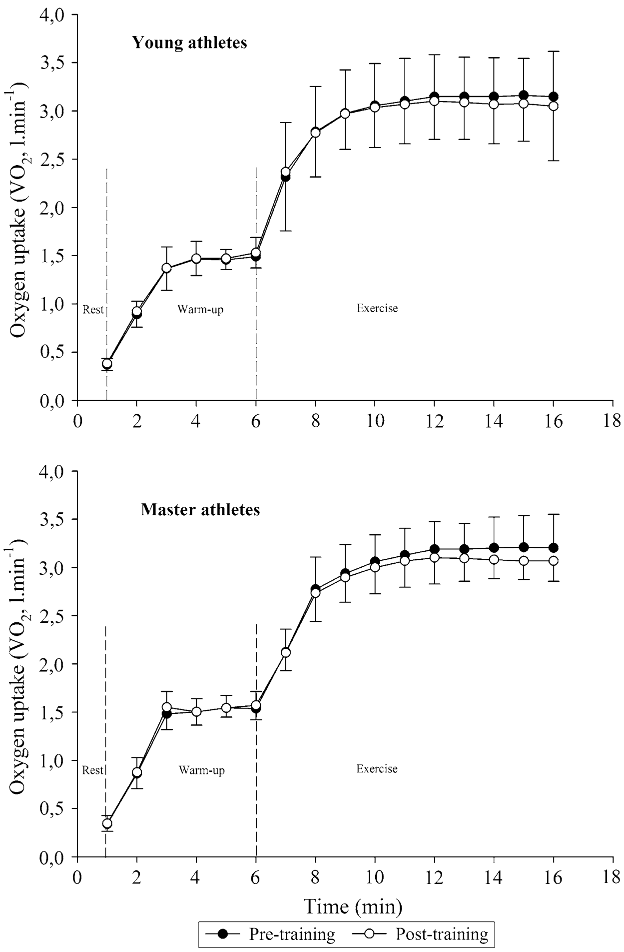

Fig. 2 Min-by-min oxygen uptake (VO_2, l min^{-1}) responses during cycling exercises performed by young and master athletes, before and after the 3 weeks strength training period. *Rest* VO_2 values recorded at rest before exercise, *Warm-up* VO_2 values recorded during the 5 min *warm-up* period at 100 W, *Exercise* VO_2 values recorded during the 10 min constant relative load period

energetic value of oxygen based on the RER value. To minimize a potential influence of the VO_2 slow component, which might vary between subject groups, the mean EE of the last 2 min of exercise was used in the calculation of DE (Fig. 2).

Statistical analysis

All data were expressed as mean ± standard deviation (SD). A two-way analysis of variance (group × session) for repeated measures was performed, in order to analyze the effect of "groups" and "strength training" on the dependent variables, MVC torque, *T*mean, delta torque, FI, and cycling efficiency. The Newman–Keuls post hoc test was used to determine any differences in training sessions and groups. Correlations between dependant variables (MVC torque and cycling efficiency) were determined using Pearson's correlation test. For all the statistical analyses, a $P < 0.05$ value was accepted as the level of significance.

Results

Muscle strength

Before training intervention, MVC torque values of young subjects were significantly higher than the masters (mean difference +17.9%, $P < 0.05$). This difference in muscle strength was reduced at the end of training period (mean difference: +7.8%, NS). In both the groups, MVC torque significantly increased after training (+17.8 ± 12.9% in masters, and +5.9 ± 11.8% in young), without age-related difference (Fig. 3).

Before training (Pre) the mean torque (*T*mean) developed by young subjects over the 30 contractions of End exercise was significantly higher than masters (mean difference +21%, $P < 0.05$). This age-related difference was reduced after the last week of training (mean difference +14.1%, NS). *T*mean significantly increased only in master athletes through the training (+6.9 ± 8.1% in masters, $P < 0.05$ and +1.8 ± 8.1% in young, NS). Moreover, the delta torque and fatigue index (FI) of the End strength test remained significantly lower in masters than the young over the training period (see Table 2 for significant differences).

Cycling efficiency

Metabolic data recorded during the cycling exercises performed before and after the training intervention indicate a significant difference in DE between the age groups. DE in cycling was higher in young when compared with masters before the training intervention (mean difference +10.7%, $P < 0.05$). However, this age-related difference disappeared after the training period (mean difference +0.15%, NS). For masters, the increase in DE after training was associated with a significant reduction in heart rate (−3.0%, $P < 0.05$), and a trend to lower minute ventilation (Table 3).

Correlation between maximal strength capacity and cycling efficiency

Figure 4 presents a significant positive correlation ($r = 0.62$, $P < 0.05$) between MVC torque and DE values recorded throughout the experiment for all the subjects (young and masters). When considering age groups, a strong significant correlation was observed in masters

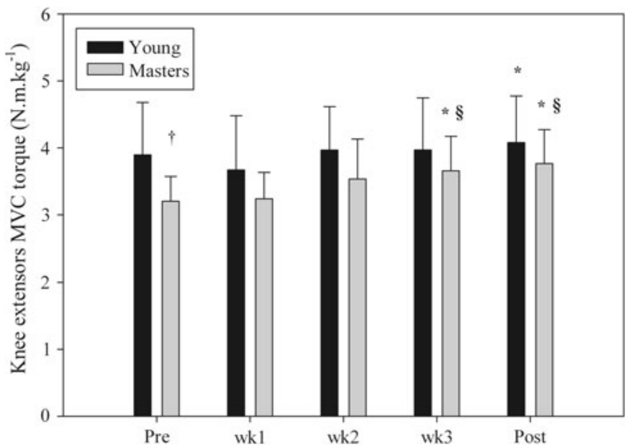

Fig. 3 Isometric maximal voluntary contraction torque (MVC torque, N m kg^{-1}) of knee extensor muscles, in master and young athletes through the training period (values are expressed as mean ± SD). *Significantly different from Pre condition, †significantly different from young, §significantly different from week1 condition ($P < 0.05$)

($r = 0.79$, $P < 0.01$) whereas it was only a trend in young ($r = 0.42$, NS).

Discussion

The aim of the present study was to test the effect of a heavy strength training program of lower limbs on muscle strength and cycling efficiency in young and master athletes. To our knowledge, this study is the first to implicate endurance master athletes in rigorous strength training, allowing the analysis of physiological adaptations of training in middle-aged athletes. Data recorded before the training intervention indicated age-related differences in cycling efficiency, maximal and endurance torque generating capacities, values being greater for young athletes. As expected, the strength training had a global beneficial effect on physical performance in both the groups. In young athletes, maximal voluntary contraction torque was increased after the training period. In masters, the strength training induced an enhancement in maximal and endurance torque production and cycling efficiency, thus reducing age-related differences in performance recorded before training.

As expected, the data recorded before the strength training intervention indicated significant differences between groups. MVC torque of the knee extensor muscles was 17.9% greater in young than the masters. This result is in accordance with previous results that indicate a significant decrease in maximal torque production with aging, despite the regular endurance training (Bieuzen et al. 2010; Louis et al. 2009). Many structural modifications in the muscle tissue induce an inevitable decline in muscle torque with aging among them; a decrease in muscle cross-sectional area (Hakkinen and Keskinen 1989) and a modification in muscle fiber composition toward a lower contraction phenotype [type II toward type I (Lexell 1995)]. Analog to MVC torque, mean torque developed over the 30 contractions of the End exercise was greater in young than the masters in pre training (*T*mean +21% for young than the masters) confirming a significant decline in muscular performance with aging. More surprisingly, indices of muscle fatigue (Table 2) indicate the development of less muscle fatigue in masters

Table 2 Mean torque and fatigue indexes during the End test in masters and young through the training period

	Pre	Week 1	Week 2	Week 3	Post
*T*mean (N m kg^{-1})					
Masters	1.24 ± 0.16†	1.19 ± 0.15	1.29 ± 0.16†	1.30 ± 0.13†	1.34 ± 0.15*,§
Young	1.50 ± 0.25§	1.38 ± 0.26*	1.55 ± 0.27§	1.59 ± 0.23§	1.53 ± 0.25§
Delta torque (N m kg^{-1})					
Masters	−0.27 ± 0.12	−0.30 ± 0.15†	−0.28 ± 0.16†	−0.30 ± 0.13†	−0.30 ± 0.14
Young	−0.43 ± 0.22	−0.42 ± 0.14	−0.48 ± 0.13	−0.53 ± 0.10	−0.48 ± 0.26
Fatigue index (FI, %)					
Masters	20.3 ± 6.7	20.4 ± 8.8	18.7 ± 9.1†	20.3 ± 7.7†	19.9 ± 8.4†
Young	26.2 ± 9.4	25.9 ± 6.5	26.6 ± 5.3	28.4 ± 4.0	30.0 ± 7.7

Values are expressed as mean ± SD

Tmean (N m kg^{-1}) mean of the maximal torque developed during the extension phase of the End test

Delta torque (N m kg^{-1}) mean difference between the last five and first five extensions

Fatigue index (%) percent decrease between the last five and first five extensions

* Significantly different from Pre condition ($P < 0.05$)

† Significantly different from young ($P < 0.05$)

§ Significantly different from week1 condition ($P < 0.05$)

Table 3 Mechanical, metabolic and cardio-respiratory parameters recorded for submaximal constant cycling exercises performed before (pre) and after (post) the training period, in masters and young

	Pre		Post	
	Masters	Young	Masters	Young
Mechanical parameters				
P warm-up (W)	100.0 ± 0.0	100.0 ± 0.0	100.0 ± 0.0	100.0 ± 0.0
P exercise (W)	220.6 ± 20.5	228.4 ± 59.7	220.6 ± 20.5	228.4 ± 59.7
Cadence warm-up (rpm)	80.2 ± 1.3	81.0 ± 1.3	80.1 ± 1.6	80.7 ± 1.2
Cadence exercise (rpm)	79.6 ± 1.2	80.4 ± 1.7	80.0 ± 1.7	80.8 ± 0.9
Metabolic parameters				
VO_2 warm-up (l min^{-1})	1.55 ± 0.11	1.49 ± 0.13	1.56 ± 0 .12	1.51 ± 0.11
VO_2 exercise (l min^{-1})	3.32 ± 0.27	3.20 ± 0.42	3.12 ± 0.27*	3.16 ± 0.38
Delta efficiency (DE, %)	19.66 ± 1.31†	21.77 ± 1.38	22.86 ± 1.40*	22.66 ± 2.42
Respiratory exchange ratio	0.92 ± 0.04	0.90 ± 0.07	0.95 ± 0.05	0.92 ± 0.04
Cardio-ventilatory parameters				
Heart rate (HR, bpm)	153.2 ± 11.4	162.7 ± 10.0	148.4 ± 10.9*,†	160.1 ± 9.3
Minute ventilation (VE, l min^{-1})	91.5 ± 15.4	84.5 ± 20.4	86.4 ± 14.6	83 ± 21.6

Values are expressed as mean ± SD

* Significantly different from Pre condition ($P < 0.05$)

† Significantly different from young ($P < 0.05$)

than the young over the 30 contractions. This study is the first to record an age-related difference in muscle fatigue development during a strength endurance task in similarly trained athletes. Despite a strength loss, masters had probably developed muscular adaptations allowing them to perform the same task as young without becoming more fatigued. This might be due to a greater proportion of muscle type I fibers, which are more resistant to fatigue (Lexell 1995). In this study, delta efficiency in cycling was greater in young (+10.7%) than the masters before the strength training. This conflicts with a recent literature review of Tanaka and Seals (2008), who reported no age-related differences in locomotion efficiency. The main hypothesis evocated was that the maintenance of muscle fiber type throughout the aging process could contribute to preserving exercise economy in master athletes. Our results are not in agreement with this assumption showing: first, significant differences between young and masters in delta efficiency and finally, in cycling, strength production was highly correlated with efficiency in master athletes ($r = 0.79$). In this context, the inevitable torque loss recorded with aging could induce a significant alteration in muscular efficiency in master athletes. These results are in agreement with a recent study by Sacchetti et al. (2010), who also reported a significant reduction in cycling efficiency in master athletes (65.6 ± 2.8 years) when compared to similarly trained young subjects (24.3 ± 5.3 years). Therefore, these results suggest that strength training added to endurance training might be a complementary strategy to preserve functional capacity and performance with aging.

The effect of strength training protocols on physical performance has been widely studied in sedentary or little active middle-aged and elderly people (Macaluso and De Vito 2004). All the results indicate significant improvements in strength production, simplifying daily life activities and thus increasing well-being (Macaluso and De Vito 2004). An increase in maximal strength production following several weeks of strength training would be likely related to neural adaptations, allowing muscle fiber recruitment to be more efficient (i.e., spatial and temporal recruitments), and better coordination between the muscles acting in strength production (Hakkinen et al. 1998a; Macaluso and De Vito 2004). Moreover, some results from literature have shown that structural modifications of muscle tissues could also occur within the hours following the training, like an increase in protein synthesis stimulating the development of muscle fibers, and especially type II muscle fibers (Chesley et al. 1992; MacDougall et al. 1992). The present study is the first to test the effect of strength training on master athletes regularly trained in endurance. Based on previous studies, our master athletes were engaged in rigorous strength training with heavy training loads (70% 1RM, [Holm et al. 2008]). As previously reported in studies using a similar training protocol, significant performance improvements were recorded in both the groups after the 3 weeks of strength training. In our study, MVC torque increased by 17.8% in masters and

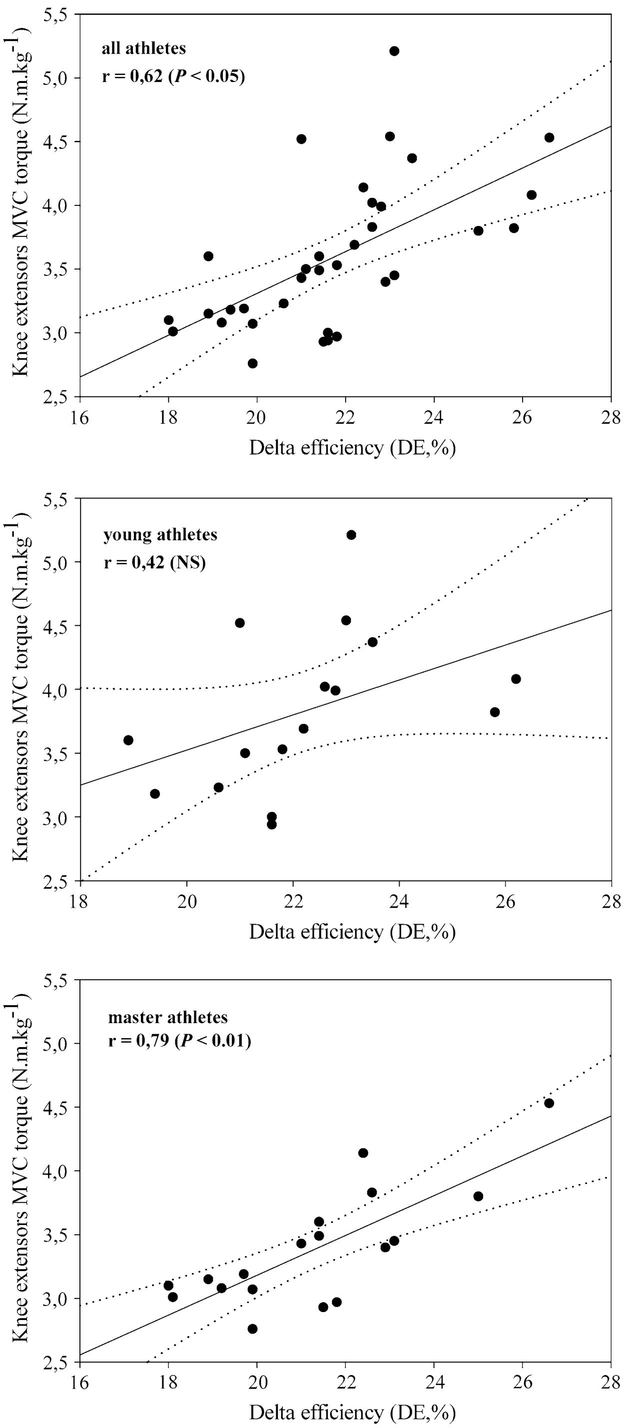

Fig. 4 Relationship between delta efficiency (DE, %) in cycling and knee extensors maximal voluntary contraction torque (MVC torque, N m kg^{-1}) through the experimentation, in all the athletes, young, and masters. *Dotted lines* correspond to 95% confidence intervals, around the mean (the *solid line*)

5.9% in young in the post condition. Using a similar strength training protocol for the knee extensors, Holm et al. (2008) recorded a 15% increase in MVC torque of young untrained subjects (25 ± 1 years). In aged sedentary people (>60 years), Frontera et al. (1988) and Hakkinen et al. (1998b) recorded a ∼17% increase in MVC torque after 12 weeks and 10 weeks of knee extensor's strength training (3 session/week at 80% 1RM). Interestingly, in our study MVC torque increased earlier in masters (Week 3) than in young (Post). This was probably related to the lower MVC torque starting level of masters. On the contrary, *T*mean over the 30 contractions of the End test increased significantly in young from week 2 to post training while this increase was only significant post training in masters. In both the groups, fatigue indices (i.e., delta torque, and FI) were not affected by the training protocol. An increase in strength production capacity may result in fewer muscle fibers recruited or muscle fibers working at a smaller percentage of their maximum strength to perform the same exercise. This in turn might delay the fatigue of individual motor units and allow the recruited fibers to maintain strength production (Loveless et al. 2005). The absence or delay of muscle fiber fatigue could also explain the improved exercise economy, since the efficiency of a muscle fiber is reduced following a moderate level of fatigue (Barclay, 1996).

After the training period, DE in cycling was significantly increased in masters (+13.8%, $P < 0.05$), whereas it was only a trend in young (+4.1%, NS). DE is considered by many authors as the most relevant indicator of muscular efficiency in cycling and, thus one of the best determinants of endurance performance (Coyle et al. 1992; 2005; Gaesser and Brooks 1975). It is, therefore, used to detect the performance improvement in cyclists over the competitive season or after training periods (Coyle 2005; Mogensen et al. 2006; Santalla et al. 2009). In the literature, a majority of studies report an overall beneficial effect of supplementing endurance training with strength training in young individuals (Hoff et al. 2002; Sunde et al. 2010; Tanaka and Swensen 1998). Within this framework, the principal aim of the present study was to test the possibility of improving locomotion efficiency through the strength training in middle-aged endurance athletes. The +13.8% improvement of DE in master athletes confirms the effectiveness of the strength training protocol used in this study. Results from previous studies suggest a positive relation between cycling efficiency and neuromuscular adaptations from the strength training (Hakkinen et al. 1998a; Loveless et al. 2005). Neural adaptations would increase the muscle torque development (Aagaard et al. 2002; Hakkinen et al. 1998a, b) and stability of movement coordination (Carroll et al. 2001), and potentially increase fatigue resistance (St Clair Gibson et al. 2001). Such changes in neuromuscular function and control could possibly change metabolism within the exercising muscles causing a reduced O_2 cost of cycling and this would improve cycling economy. In our study, the improvement of DE could be partly explained by the increase in maximal strength capacity (+17.8% for MVC torque, and +6.9% for *T*mean). An increase in maximal strength capacity would effectuate a reduction of the relative torque needed for each movement cycle—a lower percentage of maximal torque of the lower limb extensors would be taxed in each movement cycle—thus, lowering the actual demand of motor units recruited (Hoff et al. 2002). Moreover, results indicate a strong significant correlation between MVC torque and DE in masters (Fig. 4) suggesting a positive relation between the strength gain and DE improvement. Similarly, Sunde et al. (2010) recently recorded a significant correlation between the maximal rate of torque development and cycling efficiency in the young individuals. Bastiaans et al. (2001) also hypothesized that a reduced recruitment of type II fibers during cycling would result in a higher economy because cycling economy is related to the percentage of type I fibers in the active muscle (Coyle et al. 1992). In addition to the increase in MVC torque, the maximal strength training program used in the present study may have caused a delay in type I fiber fatigue, reducing the recruitment of type II fibers and in turn improving cycling efficiency. This leads to the conclusion that DE in cycling would be partly dependent of the maximal strength capacity in master athletes. Since the efficiency seems to decline with aging in endurance master athletes (Sacchetti et al. 2010), the addition of regular strength training to unique endurance training could constitute a favorable combination to maintain strength production and muscular efficiency.

Conclusion

In conclusion, the purpose of this study was to test the effectiveness of a three-week intensive strength training program of the knee extensor muscles in improving muscular performance in young and master athletes. This study is the first to include two age groups of endurance athletes with similar training levels. As expected, data recorded before strength training began indicated lower muscular strength and cycling efficiency in master athletes than in their young counterparts. After training, the age-related differences in maximal torque generating capacity and DE were reduced, verifying the beneficial effect of combined strength and endurance training in middle-aged athletes.

Ethical standards These experiments were conducted according to the Helsinki Declaration (1964: revised in 2001) and the protocol was approved by the local Ethics committee.

Conflict of interest The authors declare that they have no conflict of interest.

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