ORIGINAL ARTICLE

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Quadriceps maximal power and optimal shortening velocity in 335 men aged 23–88 years

Abstract The ability to develop adequate quadriceps muscle power may be highly predictive of subsequent disability among older persons. Rate as well as quantitative (sarcopenia) and qualitative (among other slowing of muscles) contributors to that age-related power decline are poorly known. The relationship of quadriceps maximal short-term power (P_{max}) and corresponding optimal shortening velocity (v_{opt}) with age was assessed in 335 healthy men aged 23–88 years. The P_{max} and v_{opt} were measured on a friction loaded non-isokinetic cycle ergometer. Anthropometric dimensions were used to estimate lean thigh volume (LTVest) and quadriceps mass. The decline in P_{max} across the adult life span (10.7% per decade) was greater than the usually reported decrease in maximal muscle strength. Power decreased already after the fourth decade. Both muscle mass (4.1% decline for LTVest or 3.4% for quadriceps mass per decade) and v_{opt} (6.6% decline per decade) contributed to the decrease in power. Age contributed to the variability in P_{max} independently to the LTVest/ quadriceps mass and v_{opt}. The age-related decrease pattern of P_{max} reflects both stabilization (or even increase) of anthropometric measures (LTVest or quadriceps mass) from youth to middleage and systematic decline of v_{opt} already from the thirties. This implicates more focus on velocity-orientated training as a means of enhancing leg power and improving functional status.

Keywords Ageing · Muscle · Exercise · Training · Peak anaerobic power

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Introduction

Skeletal muscle function becomes gradually impaired with advancing age (Marcell 2003). The relative contribution of the progressive reduction of muscle mass (sarcopenia) and decreasing muscle quality to this age-related decline in muscle performance remain uncertain (Metter et al. 1999). Loss of muscle mass is caused by age-associated atrophy and loss of fibres (Doherty 2003; Deschenes 2004). Age-related decrease in muscle quality (strength per unit of cross sectional area or strength per unit muscle mass) is attributable to preferential atrophy of type II fibres and changes in neural drive (decreases in maximum voluntary activation and changes in agonist/ antagonist coactivation). A decrease in myosin concentration, alterations in excitation–contraction coupling, a decrease in the percentage of strongly bound acto-myosin interactions and lower maximum shortening velocity due to changes in the properties of myosin have been proposed to contribute to age-related decreased muscle quality at the single fibre level (D'Antona et al. 2003).

The majority of studies investigating age-related changes in muscle function have assessed the muscle mass and strength (force). However, most habitual daily activities require power, e.g. both force and some speed of movement. Changes in single fibres together with preferential denervation and atrophy of fast motor units cause age-associated slowing of muscles (Davies et al. 1986; D'Antona et al. 2003). Therefore, the decline of maximal short-term power (P_{max}) with age is greater and probably more closely related to the loss of functional abilities than the decrease of maximal muscle strength (Young and Skelton 1994; Pearson et al. 2002; Bean et al. 2003). Quadriceps muscle performance is of particular importance in daily activities (Guralnik et al. 1995). Limited data suggest that ageing is associated with a decrease in the optimal shortening velocity (v_{opt}), i.e. velocity corresponding to maximal power abilities in the muscles of lower limb (Kostka et al. 1997; Bonnefoy et al. 1998). Decreased quadriceps muscle v_{opt} and P_{max}

may cause gradually impaired functioning, and due to this impairment, many elderly subjects are approaching or reaching functional-limitation threshold (Ferrucci et al. 1997).

Only a few studies have dealt with the loss of quadriceps P_{max} and υ_{opt} with age. The rate and pattern of decline during adulthood as well as its determinants are poorly known (Kostka et al. 2000a, 2000b). The aim of this study was to estimate the relationship of P_{max} and υ_{opt} with age in a large cohort of healthy men.

Methods

The study was conducted in the group of 335 community-dwelling male volunteers aged 23–88: either students of the Medical University ($n = 18$) or patients ($n = 317$) attending the Healthy Men Clinic at the Department of Preventive Medicine of the Medical University of Lodz (Poland) during 1999–2003 period. All the volunteers underwent physical examination prior to the study. Subjects who demonstrated any serious illness or abnormality that would influence exercise test (included chronic pain and biomechanical limitations at articular level) were excluded. Of the initial 427 men, who in the period 1999–2003 attended the Healthy Men Clinic, 110 either did not volunteer or were excluded from participation in power testing. In the oldest age group (80–89.9 years) participation rate was the lowest (15 subjects from 29 patients initially invited to the Clinic). Therefore, 317 eligible volunteers attending the Healthy Men Clinic finally participated in the study. They were predominantly (in over 85% of cases) white-collar workers with a university or secondary education level, whose occupational activity was low. All the participants were either sedentary or had been involved in recreational non-competitive sports activities of endurance type, such as walking, running, cycling, swimming or basketball (Drygas et al. 2000). All the subjects were fully familiarised with the protocol of the study. The study has been approved by an ethical committee and written informed consent was obtained from all the subjects.

Anthropometric data

Thigh muscle plus bone volume (estimated lean thigh volume—LTV_{est}) was calculated using the thigh length, three circumferences and two skinfold measurements (Jones and Pearson 1969). This anthropometric approach was validated against magnetic resonance imagery (Martin et al. 2000). Quadriceps muscle mass (M) was calculated from a regression equation derived from autopsy studies ($M = 0.307$ LTV_{est} + 0.353) (Andersen and Saltin 1985). This anthropometric approach was validated against computer-assisted tomography (Saltin 1985). The term "quadriceps' mass" is used in the present study and denotes the sum of mass of two quadriceps muscles.

Power testing

Mechanical measurements were performed on a friction-loaded cycle ergometer (Monark type 818E, Stockholm, Sweden) as previously described (Arsac et al. 1996; Kostka et al. 1997). Briefly, the ergometer was instrumented with a strain gauge (FN3030 type, 20daN, FGP Instrumentation, France) and with an incremental encoder (Hengstler type RIS IP50, 100pts/turn, Aldingen, Germany) for measurement of the friction force applied by the tension of the belt that surrounds the flywheel, and the flywheel displacement, respectively. The strain gauge was calibrated with a known mass (2.553 kg). Flywheel inertia was calculated using the method proposed by Lakomy (1986). Thus, the acceleration balancing load was added to the friction load for force computations. Instantaneous pedalling velocity (υ), force (F) and power output (P) were calculated each 5 ms and then averaged over each downstroke period. For all experiments the saddle height was adjusted to give optimal comfort for each subject and toe clips were removed to prevent any pulling action of the contralateral leg. The subjects were first familiarised with the ergometer by 5 min of submaximal cycling (0–60 W elderly and 60–150 W younger men) and sprints of 3–4 s against different friction loads. After stretching and 5-min rest the subjects were asked to perform two 8-s sprints from standardised starting position, each separated by at least 5-min rest. Friction loads were 0.25 N kg^{-1} and 0.45 N kg^{-1} of body mass (Bonnefoy et al. 1998) except the oldest men (80–89.9 years) in whom friction loads of 0.25 N kg^{-1} and 0.35 N kg^{-1} of body mass were used based on previous experience in older women (Kostka et al. 1997). At the signal given by the investigator, the subjects were asked to pedal as fast as possible until told to stop (after 8 s). During the effort, each subject was vigorously encouraged. One sprint provided as many F–υ–P combinations as pedal downstrokes (about 20). The υ–P combinations obtained during two sprints were fitted by a least square mathematical procedure to establish the υ–P relationship (Arsac et al. 1996). The highest value of P (maximal short-term power–P_{max}) and velocity at maximal power (optimal velocity–υ_{opt}) were calculated from a third-order polynomial function. Maximal power is expressed as relative to body mass–$P_{max/kg}$ (W kg^{-1}), to lean thigh volume (P_{max}/LTV_{est}), and relative to mass of two quadriceps muscles—$P_{max/Quadr}$ (W kg_{Quadr}^{-1}). The υ_{opt} is expressed as rate per minute (rpm).

Statistical analysis

Subjects were grouped by decade. The one-way analysis of variance (ANOVA) was used for comparisons

between age groups with Bonferroni post hoc testing. Different linear and curvilinear regression models were used to select best fitting models for the relationships between anthropometric and ergometer measurements with age. Multiple stepwise linear regression was performed with P_{max} as a dependent variable against age and anthropometric and ergometer measurements. Computations were made using Statgraphics Plus 5.0 (Statistical Graphics Corp.). Results are presented as mean $\pm$ SD. The limit of significance was set at $P = 0.05$ for all the analyses.

Results

Table 1 shows age, selected anthropometric characteristics, υ_{opt} and power measurements in different age groups as well as relative age-related changes in comparison with the 20–29.9 age group. Body mass was similar in older groups as compared to the 20–29.9 age group, however, was significantly lower in the three oldest groups in comparison with the heaviest 50–59.9 age group. The LTV_{est} and quadriceps' mass were lower in the three oldest groups as compared to the 20–29.9 age group. The υ_{opt} decreased systematically and was already lower in the 30–39.9 age group as compared to the youngest men. The P_{max}, $P_{max/kg}$, P_{max}/LTV_{est} and $P_{max/Quadr}$ decreased similarly with age reaching significantly lower levels at the age group 40–49.9 as compared to the youngest men.

In order to select an appropriate model for the relationship of all anthropometric and ergometer variables with age, different models were compared. The second-order polynomial model best fitted the relationship of body mass, LTV_{est} and quadriceps' mass with age:

Body mass = $66.0 + 0.843$ age $- 0.0096$ age^2
($R^2 = 8.3\%$; $P < 0.001$),
$LTV_{est} = 5.92 + 0.0313$ age $- 0.000555$ age^2
($R^2 = 18.4\%$; $P < 0.001$),
Quadriceps' mass = $4.21 + 0.024$ age $- 0.00038$ age^2
($R^2 = 17.9\%$; $P < 0.001$) (Fig. 1).

According to these regressions, body mass peaked at the age of 43.9 years, LTV_{est} at the age of 28.2 years and quadriceps' mass at the age of 31.6 years. The linear regression model best fitted the negative relationship of υ_{opt} and power measurements with age. The regression equations were as follows:

υ_{opt} (rpm) = $137.8 - 0.706$.age
($R^2 = 40.8\%$; $P < 0.001$) (Fig. 2),
P_{max} (W) = $1062 - 8.67$ age
($R^2 = 54.4\%$; $P < 0.001$) (Fig. 3),
$P_{max/kg}$ (W kg^{-1}) = $12.4 - 0.0941$ age
($R^2 = 46.5\%$; $P < 0.001$),
P_{max}/LTV_{est} (W L^{-1}) = $158.2 - 1.057$ age
($R^2 = 39.1\%$; $P < 0.001$),
$P_{max/Quadr}$ (W kgQuadr^{-1}) = $221.4 - 1.555$ age
($R^2 = 45.4\%$; $P < 0.001$).

Table 1 Mean and standard deviation (mean $\pm$ SD) of age, selected anthropometric characteristics, υ_{opt} and power measurements in different age groups as well as relative age-related changes in comparison with 20–29.9 age group

| Variable	20–29.9 (n=21)	30–39.9 (n=17)	40–49.9 (n=63)	50–59.9 (n=94)	60–69.9 (n=73)	70–79.9 (n=52)	80–89.9 (n=15)
Age (year)	25.3±1.6	34.7±2.8*	46.1±2.5*	54.7±2.6*	64.7±2.9*	73.3±2.5*	83.3±2.7*
Body mass (kg) (%)	81.7±10.4 (100)	82.7±17.4 (101.2)	82.8±12.0 (101.3)	85.9±13.8 (105.1)	78.6±13.6 (96.2)	75.5±9.0 (92.4)	71.1±9.4 (87.0)
LTV_{est} (L) (%)	6.24±0.91 (100)	6.58±1.06 (105.4)	6.09±1.10 (97.6)	6.11±0.96 (97.9)	5.53±0.77* (88.6)	5.16±0.72* (82.7)	4.75±1.00* (76.1)
Quadriceps' mass (kg) (%)	4.49±0.59 (100)	4.75±0.66 (105.8)	4.44±0.68 (98.9)	4.46±0.59 (99.3)	4.11±0.48* (91.5)	3.87±0.44* (86.2)	3.62±0.62* (80.6)
υ_{opt} (rpm) (%)	120.0±8.7 (100)	112.6±12.6* (93.8)	107.1±11.0* (89.3)	97.9±11.1*(81.6)	91.5±12.7* (76.3)	88.5±13.1* (73.8)	73.9±18.1* (61.6)
P_{max} (W) (%)	808±121 (100)	775±126 (95.9)	666±120* (82.4)	603±111* (74.6)	497±108* (61.5)	419±95* (51.9)	306±161* (37.9)
$P_{max/kg}$ (W kg^{-1}) (%)	9.96±1.33 (100)	9.57±1.69 (96.1)	8.11±1.43* (81.4)	7.15±1.49* (71.8)	6.41±1.26* (64.4)	5.63±1.48* (56.5)	4.30±1.99* (43.2)
P_{max}/LTV_{est} (W L^{-1}) (%)	131.2±21.7 (100)	118.7±14.7 (90.5)	111.1±19.9* (84.7)	100.0±18.7* (76.2)	90.2±16.9* (68.8)	82.1±19.3* (62.6)	63.5±25.2* (48.4)
$P_{max/Quadr}$ (W kgQuadr^{-1}) (%)	182.0±28.5 (100)	163.7±18.8 (89.9)	151.3±25.0* (83.1)	136.2±23.7* (74.8)	121.0±22.6* (66.5)	109.1±24.7* (60.3)	83.0±34.2* (45.6)

Difference with 20–29.9 age group: *$P < 0.05$
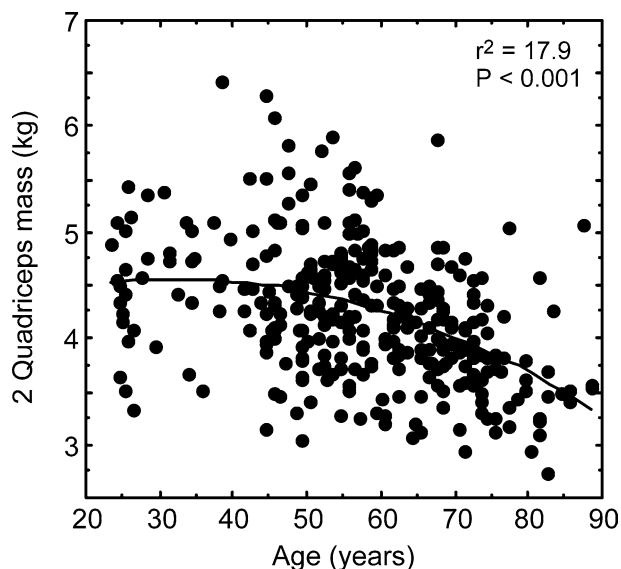
Fig. 1 The relationship of quadriceps' mass and age in 335 men aged 23–88 years
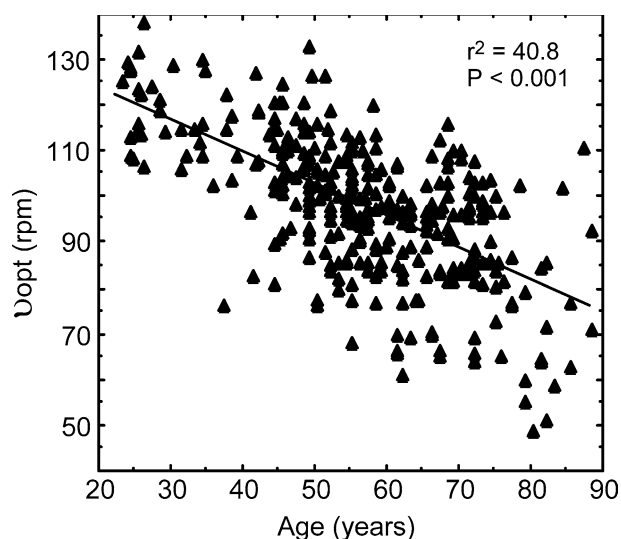

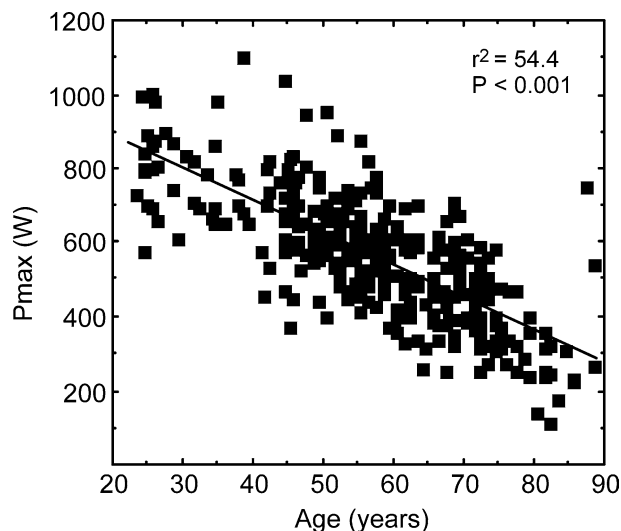**Fig. 2** The relationship of quadriceps optimal shortening velocity (υ_{opt}) and age in 335 men aged 23–88 years

Fig. 3 The relationship of quadriceps maximal short-term power (P_{max}) and age in 335 men aged 23–88 years

All independent variables (age, body mass, LTV$_{est}$, quadriceps' mass and υ_{opt}) were used in a multiple forward stepwise regression analysis to select variables influencing P_{max}. Age, body mass, LTV$_{est}$ and υ_{opt} contributed significantly to P_{max} variance and explained together 78.4% of the variability in P_{max}.
υ_{opt} was the first selected variable and explained 57.4% of the variability in P_{max}:

$$P_{max} = -216.9 + 8.01\upsilon_{opt} \ (R^2 = 57.4\%; \ SEE = 109.8).$$

LTV$_{est}$ and υ_{opt} accounted for 69.8% of the variability in P_{max}:

$$P_{max} = -432.3 + 62.0 LTVest + 6.58.\upsilon_{opt}$$
$$(R^2 = 69.8\%; \ SEE = 92.7).$$

Age explained further 6.4% of the variability in P_{max}:

$$P_{max} = 55.9 - 3.98 \ age + 51.1.LTV_{est} + 4.54.\upsilon_{opt}$$
$$(R^2 = 76.2\%; \ SEE = 82.4).$$

Body mass accounted for remaining 2.2% of the variability in P_{max}:

$$P_{max} \ (W) = -113.2 - 3.59 age + 2.29 body \ mass + 34.7 LTV_{est} + 5.12.\upsilon_{opt} \ (R^2 = 78.4\%; \ SEE = 78.7).$$

Discussion

This study provides the data on P_{max} and υ_{opt} decline with age in the so far largest examined group of middle-aged and older men. The obtained data suggest that both quantitative (quadriceps' mass) and qualitative (υ_{opt}) muscle changes contribute to the quadriceps' age-related decline in short-term power. Age contributes to the variability in P_{max} independently to quadriceps' mass and υ_{opt}, reflecting probably age-related impairment of neural control to the muscular function and an increase in the proportion of connective tissue within the muscle (Akima et al. 2001). The contribution of body mass to the prediction in the variability in P_{max} may be probably explained by the fact that cycling requires the activation of not only the quadriceps muscles, but also multiple muscle groups of lower extremities (Meltzer 1996).

The mean decrease of quadriceps muscle power as measured in athletes from youth to old age has been found to be about 10% decrease per decade (Grassi et al. 1991; Ferretti et al. 1994; Chamari et al. 1995). In our previous study older men had 40.3% lower $P_{max/kg}$ than their almost 50 years younger counterparts (8.3% per decade). This decline was greater than the decrease in

quadriceps' mass (3.8% per decade) and in $P_{max/Quadr}$ (5.9% per decade) (Bonnefoy et al. 1998). In the study of Martin et al. (2000) P_{max} and $P_{max/kg}$ declined 7.5% per decade and P_{max}/LTV_{est} decreased 5% per decade. In the present study the oldest men had 62.1% lower P_{max}, 56.8% lower $P_{max/kg}$, 51.6% lower P_{max}/LTV_{est} and 54.4% lower $P_{max/Quadr}$ than their almost 60 years younger counterparts (10.7, 9.8, 8.9 and 9.4% per decade, respectively). Both muscle mass (4.1% decline for LTVest or 3.4% for quadriceps' mass per decade) and quality (6.6% decline in υ_{opt} per decade) contributed to the decrease in power. This decline is greater than the usually reported decrease in maximal strength and similar (about 1% per year) to the results of those few studies that measured maximal quadriceps muscle power (Grassi et al. 1991; Ferretti et al. 1994; Chamari et al. 1995).

Ageing is associated with a decrease of the maximal contraction speed corresponding to a given force (Davies et al. 1986). Except for our previous reports (Bonnefoy et al. 1998; Kostka et al. 2000b) and recent study of Martin et al. (2000) there are no studies investigating the υ_{opt} in older men. Slowing of υ_{opt} reflects a change in muscle quality (atrophy of type IIb fibres, probably together with other multiple mechanisms like changes in neural drive or agonist/antagonist coactivation as well as changes in myosin concentration or properties) (Hautier et al. 1996; D'Antona et al. 2003; Doherty 2003). In the study of Bonnefoy et al. (1998) the decline in υ_{opt} from youth to advanced age was 4.3% per decade. This drop was similar over the age-range of 66–84, about 0.3% per annum. In the study of Martin et al. (2000) υ_{opt} was practically unchanged in the forties age group, and then decreased approximately 8% from the 40–49 decade to the 60–69 decade. In the present study the drop in υ_{opt} was visible already in the thirties and continued systematically till the eighties. Several factors may explain these discrepancies. In the study of Martin et al. (2000) all subjects over 30 years of age were competitive cyclists. The test was of short duration (3–4 s), while in the present study, of 8 s. In the method applied in the current study, cycling power peaks usually between the fourth and the sixth second of the test. This might have permitted better development of cycling abilities and more precise measurement of υ_{opt}. A much larger number of subjects and a wider older adults' age span lend further strength to the results of the present study.

In previous the studies, the age-associated decline of muscle strength has usually been depicted as linear, piecewise or curvilinear, with an acceleration after the fifth decade (Kallman et al. 1990; Backman et al. 1995; Metter et al. 1997; Stoll et al. 2000). It has also been suggested that the drop in muscle power might accelerate in advanced age. In one available study, (Skelton et al. 1994) the differences in leg extensor power expressed per kg of body mass over the age range of 65–89 years were equivalent to losses of 3.0% per annum in healthy men. In another study, the same differences over

the age range 66–84 years were equivalent to losses of 1.5% per annum (Bonnefoy et al. 1998). In the present study, the linear regression model best fitted the relationship of P_{max} with age. The P_{max} results from muscle strength (closely dependent on muscle mass) and from muscle quality (reflected by υ_{opt}). Therefore, the age-related decrease pattern of P_{max} reflects both stabilization (or even increase) of anthropometric measures (quadriceps' mass or LTVest) from the youth to middle age (Janssen et al. 2000), and a systematic decline of υ_{opt} from the thirties. Unlike for muscle strength, power starts to decrease after the fourth decade or earlier and becomes significantly lower during adulthood. Although generally linear across the entire examined age range, the drop of P_{max} seemed to accelerate in older subjects when compared to the preceding decade and not to the 20–29 years reference values. The decline of $P_{max/kg}$ averaged 1.03% from the sixth to seventh, 1.42% from the seventh to eighth and 2.36% per annum from the eighth to ninth decade. This decline is similar to the deterioration of Olympic weightlifting ability, between 1.0 and 1.5% per year until approximately age 70, after which the rate seemed to increase (Meltzer 1994; Pearson et al. 2002). These weightlifting abilities are probably closely related to muscular power. It cannot be excluded, therefore, that even the great number of subjects participating in this study (considerably greater than in the studies with Master weightlifters) was not able to detect curvilinear character of age-related power decline (Metter et al. 1997). Whether this acceleration in power decline really exists should be further explored in future studies with even more participants aged 80–100 years.

This study has several limitations. This is a cross-sectional study and patterns of decline may be different in longitudinal comparisons. Our subjects were more healthy and fit than a random sample, especially of older people. These subjects are more prone to volunteer for such studies. The measurement of quadriceps mass by anthropometric methods did not allow the assessment of intramuscular fat and connective tissue. As the percentage of the latter increases with age the observed stabilisation or even increase in muscle mass from youth to middle age should be viewed more critically, though potential bias is rather minor (Martin et al. 2000; Akima et al. 2001). Finally, it should be stated that the collection of data in women would bring even more important information as women are at greater risk of losing independence due to insufficient locomotor system functioning. Therefore, gathering muscle power data across the lifespan in women will be even more important from the public health point of view and future studies in women are badly needed.

In conclusion, these data show that the age-related decrease pattern of P_{max} reflects both stabilization (or even increase) of anthropometric measures (LTVest or quadriceps mass) from youth to middle-age and the systematic decline of υ_{opt} from the thirties. Unlike for the majority of muscle strength data, power starts to decrease after the fourth decade and earlier and becomes

significantly lower during adulthood. This may provide rationale for more velocity-orientated training for delaying the functional decline.

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