ORIGINAL ARTICLE

Andrea Macaluso · Giuseppe De Vito

Comparison between young and older women in explosive power output and its determinants during a single leg-press action after optimisation of load

Abstract Lower limb explosive power, which is more predictive of functional difficulties than strength per se with women being more at risk than men for disability, has been previously compared between young and older women using systems with fixed inertia. Individuals may have been obliged to use a percentage of their maximum strength that is not ideal for performing the movement at the optimum speed for maximum power output. This study was designed to compare explosive power output and its two determinants, optimal force and optimal speed, during a leg-press action between young and older women after optimising the load for maximum power production. The experiments were carried out on 20 women in good physical condition: 10 older, aged between 65 and 74 years and 10 young, aged between 18 and 30. Explosive power output was measured by setting the initial load at different percentages of maximum isometric strength and measuring the corresponding speed of movement during a leg-press action of the dominant leg. Maximum peak power, which was obtained at 60% of maximum isometric strength in both young and older women, was 61% lower in the older women ($P < 0.0001$). This was due to a 52% lower optimal force ($P < 0.0001$) and 21% lower optimal speed ($P < 0.01$). The ratio of peak power to maximum isometric strength was 22.1% lower in the older women ($P < 0.01$). After optimising the load, both lower speed of movement and lower strength determine the lower levels of power in older women. Power is more affected by ageing than isometric strength.

Keywords Explosive power output · Isometric strength · Older women · Optimal force · Optimal speed

A. Macaluso (✉) · G. De Vito
Applied Physiology Group, Strathclyde Institute for Biomedical Sciences, University of Strathclyde, 76 Southbrae Drive, Glasgow, G13 1PP, United Kingdom
E-mail: andrea.macaluso@strath.ac.uk
Tel.: +44-141-9503718
Fax: +44-141-9503132

Introduction

The ability to perform physical tasks of everyday life in old age, such as rising from a chair, climbing stairs or using public transport, depends on the maintenance of critical levels of muscle strength and power (Harridge and Young 1998). Explosive power output, which can be defined as the ability to generate work over a fraction of a second, has been shown to be more predictive of functional difficulties than strength per se in older people (Harridge and Young 1998; Fiatarone Singh 2000; Foldvari et al. 2000). Its decline is particularly evident in women who have been identified as the primary target group for intervention and rehabilitation studies (Bassey et al. 1992; Skelton et al. 1994). There is evidence that explosive power output declines with ageing at a higher rate than maximum isometric strength, thus suggesting that the decreased ability to generate power is due to an inferior ability to develop both dynamic strength and speed (Davies et al. 1983; Skelton et al. 1994; Metter et al. 1997; Izquierdo et al. 1999). However, in previous studies (Bosco and Komi 1980; Davies et al. 1983; Grassi et al. 1991; Ferretti et al. 1994; Skelton et al. 1994; Metter et al. 1997; De Vito et al. 1998) explosive power output has been assessed using fixed inertia, either during a vertical jump, where the inertia was represented by the subject's body weight (Bosco and Komi 1980; Davies et al. 1983; Grassi et al. 1991; Ferretti et al. 1994; De Vito et al. 1998), or by a flywheel system (Skelton et al. 1994; Metter et al. 1997). This is a limitation because the weaker subjects may be disadvantaged, since this inertia would correspond to a high percentage of their maximum and consequently not represent the optimal value of force for maximum power production (De Vito et al. 1998; Harridge and Young 1998). In other words, when older subjects are required to push a high resistance, such as their body weight during a vertical jump or the same inertia as stronger subjects during a single leg extension on the Nottingham power rig (Bassey and Short 1990), they must use a high percentage of their

Table 1 Age, stature, body mass and quadriceps cross-sectional area (*CSA*) of the dominant limb in young and older subjects

Group	Age (years)		Stature (m)		Body Mass (kg)		CSA (cm^2)	
	Mean	(sd)	Mean	(sd)	Mean	(sd)	Mean	(sd)
Young ($n = 10$)	22.8	(5.7)	1.64	(0.05)	58.9	(11.1)	55.4	(5.4)
Older ($n = 10$)	69.5	(2.4)	1.58	(0.04)	67.5	(14.5)	41.5	(4.2)

maximum strength. Therefore, they may perform the movement at slower speed, which is away from the optimal speed for maximum power production. To the author's knowledge, there is only one study in which explosive power has been compared between middle-aged and older men after optimising the load (Izquierdo et al. 1999), but no study to date has considered this issue in women. Moreover, the two determinants of power output, i.e. optimal force and optimal speed, have not been considered.

The present study was designed to compare explosive power output and its two determinants between young and older women by assessing power at the optimal force and speed for maximum power production during a leg-press extension, which is a functional action. It is perhaps obvious that older women will be weaker and less powerful than young women, but is the inferior ability to generate power due to a lesser ability to develop force or speed or both?

Methods

Subjects

Twenty women, ten older (age range 65–74 years) and ten young (age range 18–30 years), volunteered for the study. The physical characteristics of the participants are presented in Table 1, together with values of their quadriceps cross-sectional area (CSA) of the dominant limb, determined by magnetic resonance imaging (see details below).

Subjects were selected according to the exclusion criteria to define ''medically stable'' older subjects for exercise studies, as proposed by Greig et al. (1994). Most subjects were habitually physically active, but not practising any kind of systematic training. The experimental procedures comply with the current laws in the United Kingdom and were approved by the Ethics Committee of the University of Strathclyde. All subjects gave their informed consent for participation in the study.

Maximum voluntary isometric strength and maximum power output

Subjects warmed up on an exercise bicycle for 5 min at a light resistance before performing any strength or power test. All the subjects were previously familiarised with the experimental procedures on at least one occasion, 3 or 4 days before the testing session. Both isometric and dynamic measures were made on the dominant lower limb using a dynamometer (Kin Com, Chattanooga, USA) in the leg-press position. As shown in Fig. 1, the seat was modified in order to have firm support placed behind the buttock. The trunk was fastened by three belts and each subject's leg was positioned so that a starting angle of 90° at the hip, knee and ankle joint was obtained. The other leg was kept in a neutral sitting position with the foot supported by a pedestal.

The maximum voluntary isometric strength (MVC) task consisted of rapidly increasing the force exerted during the leg-press to

Fig. 1 Dynamometer adopted to perform both isometric and power measures during the leg-press of the dominant limb. The seat was modified in order to have a firm support placed behind the buttock. The trunk was fastened by three belts and each subject's leg was positioned so that a starting angle of 90° at the hip, knee and ankle joint was obtained

a maximum. A target line was always set on the computer screen at a value 20% higher than the best performance. Subjects followed their performance on the computer screen and were verbally encouraged to achieve a maximum, in an attempt to exceed the target force, and to maintain it for at least 2 s before relaxing. The MVC was calculated as the largest 1-s average reached within any single force recording. At least three maximal attempts were performed, separated by 3 min, and the best performance was chosen as MVC. Subjects were asked to make a further attempt if the MVC of their last trial exceeded that of previous trials.

The power measures were performed setting the dynamometer in the ''isotonic'' mode, with the initial load at 40% of MVC. The test was then repeated with the initial load increased, in 10% increments, up to 80% of MVC, in a random order. Each subject was required to push forward, as strong and quickly as possible, until the leg was fully extended, throughout a range of motion of 0.2 m. Three trials for each level of initial load were performed, in a random order, with a 3-min interval between each trial. Figure 2 shows a typical example of force, speed and displacement in one of the subjects, when the initial load was set at 60% of MVC. Although the dynamometer used in this investigation has been set in the ''isotonic'' mode, it is clear that force is not kept constant during the movement, which cannot therefore be referred to as isotonic. The dynamometer attempts to hold the lever arm resistance at the user-selected level by reading the loadcell signal and adjusting the speed of the motor potentiometer throughout the full range of motion, but the sampling rate of the instrument (100 Hz) is such that the adjustment is not quick enough to obtain a constant trace. However, it must be clarified that this is not relevant to this study. In order to test the hypothesis of this investigation it was necessary to adopt a dynamometer that enabled us to measure the velocity of movement with the subjects exerting a given level of average force throughout the movement, which corresponded to various percentages of isometric force. The initial loads the subjects were asked to push were almost equal to the user-selected level, for all of the percentages of maximum force which were tested, and were highly correlated with both the forces at peak power output (PP, $R^2 = 0.98$; $P < 0.0001$) and the average forces measured during
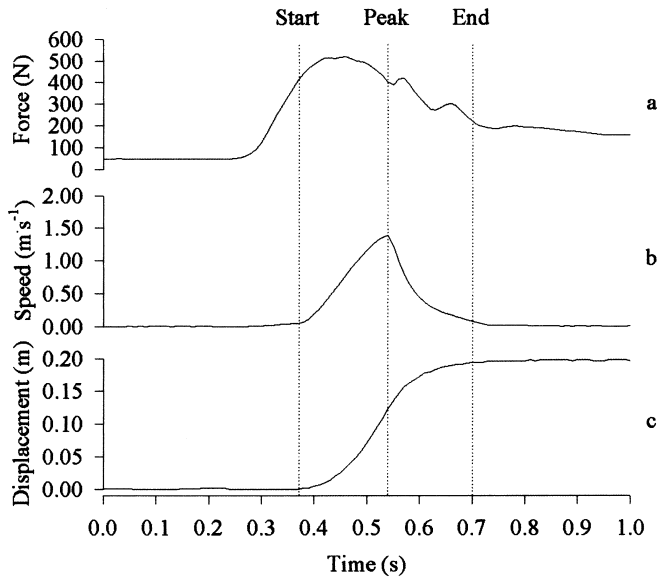
Fig. 2a–c Force (**a**) and speed of movement (**b**) during a leg-press movement plotted, along with the displacement (**c**), against time for one subject. Initial load was set at 60% of MVC (400 N). Peak power output (*PP*) was calculated as the product of the force at the instant in which it reached the user-selected level (400 N) and the corresponding speed (1.38 m·s^{-1}), that is also peak speed. Average power output (*AP*) was calculated as the mean of the instantaneous values of power during the thrust

the thrust ($R^2 = 0.97$; $P < 0.0001$). PP was calculated as the product of the force, at the instant in which it reached the user-selected level, and the corresponding speed, that is also peak speed. Average power output (AP) was calculated as the mean of the instantaneous values of power during the thrust. Repeatability of the measurements was assessed in all subjects 3 or 4 days after the testing session. Intraclass correlation coefficients in young and older subjects, respectively, were 0.91 and 0.97 for MVC, 0.91 and 0.94 for PP, and 0.91 and 0.94 for AP.

Muscle cross-sectional area

The cross-sectional area (CSA) of quadriceps muscle was measured by magnetic resonance imaging as previously described (Macaluso et al. 2002). Briefly, a 1.0T Impact Expert Scanner (Siemens, Erlangen, Germany) was used to perform T1-weighted volume acquisitions through the whole of both femurs. Images were acquired coronally to minimise artefacts from any subject movement and the three-dimensional volume acquisition was then re-cut into axial sections of 1.7 mm covering the complete length of the femur. CSA per each axial section was calculated by drawing a region of interest around the quadriceps muscle using Scion Image Analysis Software (Scion, Frederick, USA). The intramuscular non-contractile tissue (e.g., connective tissue and fat) was separated from the muscle contractile component by determining an individual threshold for pure muscle in each subject. The greatest contractile CSA of the quadriceps muscle, which is reported in Table 1, corresponded to the mid-thigh scan.

Statistics

All data were normally distributed in terms of skewness and kurtosis (all values less than |2|). Means and standard deviations (sd) are presented. Comparisons between young and older subjects were made using a two-sample Student's *t* test. Statistical significance was accepted if the two-tailed *P* value was < 0.05.
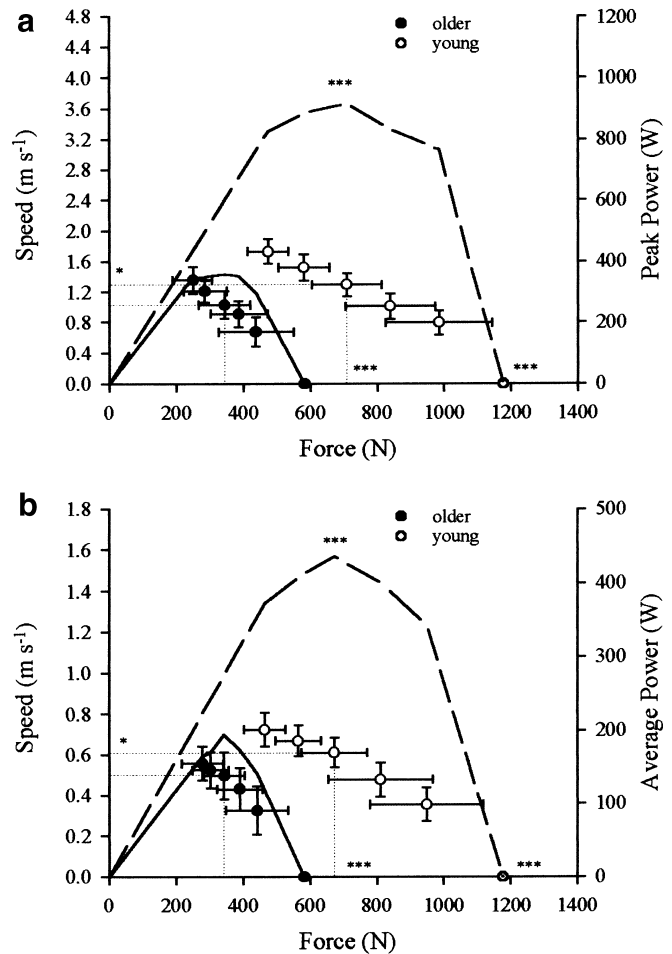

Fig. 3a, b Peak (**a**) and average (**b**) speed of movement in the young (*open circles*) and the older women (*filled circles*) plotted as a function of force at 40, 50, 60, 70 and 80% of maximum isometric force (*MVC*). Data are expressed as means (sd). The *dotted line* represents the corresponding power output in the young women and the *solid line* in the older women. Optimal speed and optimal force at peak power (*PP*) (**a**) and average power (*AP*) (**b**) are highlighted. ***$P < 0.0001$; *$P < 0.01$ significantly different from older women

Results

Figures 3a and 3b show the results of PP and AP, respectively, with the corresponding values of speed and force at PP and AP, for the different initial loads, and MVC, in young and older individuals.

Force is plotted on the x-axis, because the independent variable is the load the subjects have to work with, as is the case in real life. Both maximum PP and AP were reached when the initial load was set at 60% of MVC and these values were used for the statistical comparison between young and older women. The older women generated 60.9% less maximum PP [358 (115) vs. 917 (168) W; $P < 0.0001$], 55.3% less maximum AP [195 (86) vs. 436 (95) W; $P < 0.0001$] and 50.4% less MVC [583 (105) vs. 1177 (180) N; $P < 0.0001$] than the young women. Both maximum PP and AP were generated by
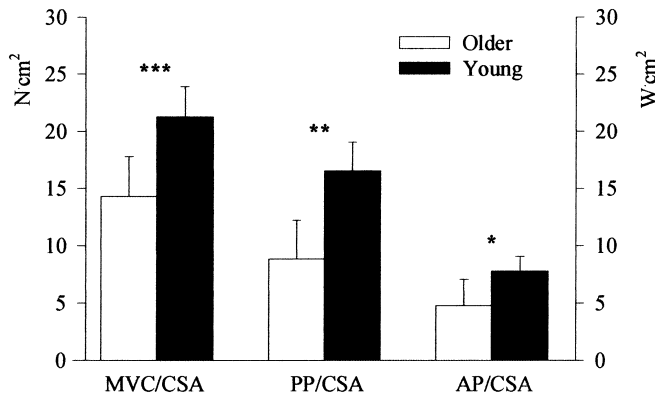
Fig. 4 Maximum isometric force (*MVC*), peak power (*PP*) and average power (*AP*) normalised to quadriceps cross-sectional area (*CSA*), in young and older women. Data are expressed as means (sd). *$P < 0.01$; **$P < 0.001$; ***$P < 0.0001$ significantly different from older women

pushing a significantly lower peak [344 (77) vs. 709 (104) N; $P < 0.0001$] and average [343 (61) vs. 673 (98) N; $P < 0.0001$] optimal force and achieving a significantly lower peak [1.03 (0.18) vs. 1.29 (0.15) m·s^{-1}; $P < 0.01$] and average [0.50 (0.12) vs. 0.61 (0.07) m·s^{-1}; $P < 0.01$] optimal speed, respectively, compared to the young women. Figure 4 shows that after normalisation for quadriceps CSA of PP, AP and MVC, there was still a significant difference ($P < 0.0001$ for PP; $P < 0.01$ for AP; $P < 0.001$ for MVC) in all of these parameters between young and older subjects.

The ratio between PP and MVC was significantly lower ($P < 0.01$) in the older [0.61 (0.15)] than the young women [0.78 (0.12)], thus suggesting that power is more vulnerable than strength to the ageing process.

Discussion

In the present study, for the first time, explosive power output has been compared between young and older women after optimising the load for maximum power production during a multiarticular functional gesture "in vivo", which involves the lower-limb muscles used during activities of daily living. The fact that the older women could not even push the resistance at which the young women achieved maximum power, as shown in Fig. 3, emphasises the importance of optimising the load of the measurement apparatus when measuring power in functional studies involving older individuals. It is likely that in previous studies (Bosco and Komi 1980; Davies et al. 1983; Grassi et al. 1991; Ferretti et al. 1994; Skelton et al. 1994; De Vito et al. 1998) muscle power was underestimated in older people, in that individuals were obliged to use a high percentage of their maximum strength, therefore performing the movement at slower speed, which was away from the optimal speed for maximum power production. Similarly, it is likely that maximum power was also underestimated in young individuals, in that they pushed a resistance which was lower than optimal force for maximum power production.

The inferior ability to generate explosive power was due to a lesser ability to develop both force and speed of movement, as shown in Fig. 3. In fact, optimal speed and optimal force were significantly smaller in the older women at both maximum PP (Fig. 3a) and AP (Fig. 3b). As optimal speed was measured when optimal force was the same percentage of MVC in the two groups (60%), thus standardising for differences in optimal force, it can be concluded that the older women generated less power because they were slower than the young even when using the same percentage of their maximum strength. Our finding is in contrast with the recent results of Pearson et al. (2002), who compared a population of weightlifter athletes with untrained healthy subjects by using a variable inertial testing system (Pearson et al. 2001) mounted in apparatus designed for measuring explosive power in older people (Bassey and Short 1990). In their study, weaker individuals achieved maximum power output at lower inertial loads than stronger individuals, but the speed component was found to be not significantly different between the two groups. The discrepancy with our results could be ascribed to the different study population and testing methodology. Moreover, since the inertial load was not standardised to a similar percentage of MVC in the two groups, this makes the comparison with our data even more problematic. In contrast, our data show some similarities with those of Izquierdo et al. (1999), although their measurements were carried out on individuals of different gender (male) and different age groups (middle-aged versus older). In their study, maximum average power output during a half squat, which is largely effected by the same muscle groups as investigated in our study, was measured by pushing an initial resistance equal to 60–70% of the maximum weight that could be lifted. However, Izquierdo et al. (1999) did not focus their attention on the relative role of the two determinants of power output, i.e. optimal force and optimal speed. Speed of movement can nevertheless be extrapolated from a closer analysis of their graphical results, and it is clear that the higher values of power, which were achieved by the relatively younger individuals (middle-aged men), were due to higher levels of both optimal force and optimal speed, although this was not remarked upon by the authors.

Data of force and speed plotted in Fig. 3 may be fitted by a regression curve, either of first or second order, and the MVC extrapolated from this curve would be higher than the MVC values that have been measured in this study. This could be interpreted using the fact that MVC was measured at an angle which may have been away from the optimum angle for MVC (Sale 1991). This angle is also different from that of optimal force at peak power. These results are in agreement with the findings of Rahmani et al. (2001), who have shown that the force measured during an isometric half-squat at a knee angle of 90° was different from the isometric force

extrapolated from the force–velocity relationship. However, in our study the possibility of underestimating MVC would apply to both young and older individuals, thus not affecting the relative differences in power and its determinants between the two groups, which is the main point of this investigation.

It has been established that loss of muscle mass is an important factor contributing to the reduction of muscle strength and power in older subjects (for review, see Vandervoort 2002). In our study, the smaller muscle mass did not totally explain the lower levels of strength and power, since the differences between young and older women still existed after normalisation for CSA (Fig. 4). The push phase of the leg-press movement is mainly effected by the extensor muscles of the thigh, which justifies normalisation of MVC and power values with respect to contractile CSA of the quadriceps muscle. However, this presents a limitation, because in a multiarticular gesture like the leg-press action other muscles play a role, such as the hip extensors. Furthermore, the area of muscle cross-section at right angles to the long axis of the limb, i.e. anatomical CSA, cuts through a limited number of fibres and is therefore smaller than the physiological CSA (Fukunaga et al. 1992; Narici 1999). Despite these limitations, it is reasonable to infer that the lower levels of strength and power can be mainly attributed to the selective atrophy of type II fibres (Larsson et al. 1979; Lexell et al. 1988), as type II fibres are intrinsically stronger and faster than type I fibres and therefore muscles with the same area, but occupied by a relatively smaller area of type II fibres, will be able to generate less force and speed. The selected atrophy of type II fibres is further supported by the evidence that in the older muscle there is a relative increase in slow myosin heavy chain (MHC) content (Klitgaard et al. 1990). In agreement with the results of this study is also the slowing in the contractile properties, which has been demonstrated in various muscles of the lower limbs (Vandervoort and McComas 1986; Roos et al. 1999) and in the adductor pollicis muscle (Narici et al. 1991) by measuring the duration of twitch contraction. At the microscopic level of muscle analysis, this has been ascribed to a reduction in sarcoplasmic reticulum activity (Kiltgaard et al. 1989; Delbono et al. 1997; Hunter et al. 1999) and actin sliding speed on myosin (Höök et al. 2001). The shift towards slower muscle with ageing has been confirmed by studies on the contractile mechanics of single fibres, in which it has been shown that both MHC-I and MHC-IIA single fibres have lower specific tension and maximum shortening velocity if they originate from the muscles of an older person as opposed to a young person (Larsson et al. 1997; Frontera et al. 2000). However, measurements of force and power in vivo represent the resultant of relatively complex situations, where not only the contractile elements of muscle cells must be considered, but also changes in tendon stiffness, which reduce the effectiveness of force and power transmission (Maganaris 2001), and in the neural activation of agonist muscles and coactivation of antagonist muscles (Macaluso et al. 2002). Metter et al. (1997) speculated that normal ageing changes in the basal ganglia, consisting of a continuing loss of dopaminergic neurons in the substantia nigra (Morgan et al. 1994), could be a contributor to the observed slowing in speed, coordination and power, together with peripheral changes such as slowing in nerve conduction velocities (Norris et al. 1953) and lower muscle membrane excitation (Hicks et al. 1992). These physiological factors would also explain the significantly lower ratio of PP to MVC in the older women, thus indicating that power output, which depends on both strength and speed, is lost to a greater extent than isometric strength. This is in agreement with Skelton et al. (1994), who reported a decline in average power of healthy older people aged from 65 to 89 years of 3.5% per annum as opposed to a decline in isometric strength of 1.5% per annum.

In conclusion, this study has provided new information on maximum power output and its two determinants, i.e. optimal force and optimal velocity, during a multiarticular functional action in young and older women. The older women of this study could not even move the resistance at which the young women achieved maximum power, thus revealing the importance of optimising the initial level of load in measuring power output. The inferior ability to generate explosive power is due to a lesser ability to develop both force and speed of movement. Differences in strength and power between young and older women still persist after normalisation per muscle mass, and power seems to be more vulnerable than strength to the ageing process. Further studies are required to investigate how force and speed of movement respond to resistance training programmes.

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