ORIGINAL ARTICLE

Changes in power and force generation during coupled eccentric–concentric versus concentric muscle contraction with training and aging

Paolo Caserotti · Per Aagaard · Lis Puggaard

Abstract Age-related decline in maximal concentric muscle power is associated with frailty and functional impairments in the elderly. Compared to concentric contraction, mechanical muscle output is generally enhanced when muscles are rapidly pre-stretched (eccentric contraction), albeit less pronounced with increasing age. Exercise has been recommended to prevent loss of muscle power and function and recent guidelines indicate training program for increasing muscle power highly relevant for elderly subjects. This study examined the differences in muscle power, force and movement pattern during concentric-alone and coupled eccentric–concentric contraction and selected functional motor performances before and after 36-week multicomponent training including aerobic, strength, balance, flexibility and coordination components in elderly males. Vertical force, excursion, velocity, power and acceleration of the body center of mass were measured in two standardised vertical jumps (squatting jump, SQJ; countermovement jump, CMJ). Pre-stretch enhancement during CMJ did not improve performance [i.e., no enhanced maximal muscle power (P_{peak}) and jump height (JH)] compared to concentric-alone muscle contraction (SQJ). Nevertheless, pre-stretch enhancement occurred as for similar SQJ and CMJ maximal performance, elderly people employed lower mechanical work, higher mean muscle power (P_{mean}), shorter concentric phase duration and shorter body center of mass displacement during CMJ. Post training, CMJ P_{peak}, P_{mean} and JH increased in training group ($P < 0.05$) while P_{peak} and JH decreased in control group during the CMJ and SQJ ($P < 0.05$). In conclusion, long-term training counteracted the age-related decline in muscle power and functional performance observed in the control subjects, while substantial gains in muscular performance were observed in the trained elderly.

Keywords Muscle power · Countermovement jump · Squatting jump · Elderly · Exercise

Introduction

Muscle power, the product of muscle force and contraction velocity, is continuously generated both as concentric-alone and coupled eccentric–concentric muscle contraction modes during everyday motor tasks, for example in the sit-to-stand movement and gait, respectively. Compared to concentric contraction alone where the muscle undergoes exclusively active shortening, coupled eccentric–concentric contraction is characterised by active muscle lengthening (i.e., eccentric contraction) immediately followed by active muscle shortening. Several features make this contraction type unique compared to concentric contraction alone. Coupled eccentric–concentric contractions (also called stretch–shortening cycle, SSC) involves pre-activation and variable activation of active muscles prior to concentric muscle contraction, interaction from elastic properties of the musculo-tendineous structures (length changes in muscle versus tendon) and contribution from stretch–reflex mechanisms (Bobbert et al. 1996; Finni et al. 2000; Komi 2000; Fukunaga et al. 2002). Thus, compared to concentric-alone muscle contraction SSC may result in enhanced contractile force generation, increased mechanical muscle performance, absorption of impact forces (during the eccentric phase of the

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movement) and increased movement efficiency (Bosco et al. 1987; Bobbert et al. 1996; Komi 2000).

During aging, the progressive decline in muscle power during concentric and coupled eccentric–concentric contractions has important functional consequences. Reduced muscle power has been identified as one of the key factors, which may jeopardise maintenance of mobility and independency for older individuals (Foldvari et al. 2000). Indeed, low concentric muscle power has been previously associated with increased physical frailty, dependency, postural instability and rate of falls in elderly individuals (Bassey et al. 1992; Foldvari et al. 2000; Skelton et al. 2002). Nevertheless, limited information is available on power generation capability during coupled eccentric–concentric muscle contraction in aging individuals, and in particular, whether mechanical pre-stretch enhancement and contraction efficiency are maintained with increasing age. Furthermore, results are equivocal as some studies have reported a progressive age-related loss of pre-stretch enhancement (Bosco and Komi 1980; Izquierdo et al. 1999b; Paasuke et al. 2003) while others reported this mechanism to be unaffected by the aging process (Svantesson and Grimby 1995; Lindle et al. 1997). Importantly, different testing protocols (isokinetic versus ballistic) and muscle groups (isolated single joint versus weight-bearing multi-joint) have been examined and comparison of results may therefore not be obvious (Bosco and Komi 1980; Svantesson and Grimby 1995; Lindle et al. 1997; Paasuke et al. 2003). The assessment of muscle power production and pre-stretch enhancement during weight-bearing motor tasks in elderly subjects is highly relevant as it may potentially give an important insight into the individual functional performance capability under the body weight constraint (Caserotti et al. 2001).

Strength training has been consistently recommended to prevent loss of muscle and functional independency in elderly subjects (Singh 2002) and more recently it was suggested that training programs should be tailored to increase muscle power due to the functional relevance of muscle power decline (Evans 2000; Skelton et al. 2002). Thus, despite strength training programs have been shown to effectively elicit maximal muscle power improvements in aging individuals (Izquierdo et al. 2001; Fielding et al. 2002) training programs for older individual are often designed as multicomponent training that typically consists of a combination of aerobic, strength, balance and flexibility exercises. Importantly, concurrent aerobic and strength training compared with strength training alone was previously reported to interfere with increase in explosive force capabilities assessed as rate of force development despite similar hypertrophy response and muscle strength increases occurred for both training types (Häkkinen et al. 2003). Thus, concurrent training where neuromuscular and

cardiovascular stimuli among other training stimuli (e.g., balance) are combined, may potentially limit adaptation in explosive muscle force and muscle power. Limited information is available on the effects of such multicomponent training programs on muscle power during concentric contraction (De Vito et al. 1999) and no information is available on the effects of this type of training on coupled eccentric–concentric contractions in older adults.

It was the hypothesis of the present study that (1) no or only minimal pre-stretch enhancement would be observed during coupled eccentric–concentric versus concentric-alone muscle contraction in 75-year-old elderly males, (2) long term low frequency multicomponent training would reduce the age-related decline in maximal muscle force and power production in coupled eccentric–concentric and concentric-alone muscle contraction, and that (3) these training-induced changes would translate into improvements in selected functional motor performances.

Methods

Subjects

After approval of the local ethical committee, community-dwelling healthy males, 75 years old, all residents in the city of Odense, Denmark were recruited. This study is a part of a larger study and recruitment procedure has been earlier reported (Puggaard 2003). In brief, names and addresses from age-cohort of 1922 were extracted from the register of the Danish national civil registration number (CPR). Subjects were contacted and those who agreed to participate gave their informed consent, were interviewed and medically screened. The latter consisted of resting electrocardiogram and anamnesis to exclude any disease that could interfere with the research protocol. From the eligible 161 male subjects, 44 subjects were randomly selected and divided for the present study into a training group (TG, $n = 16$) and a control group (CG, $n = 28$) group. To be eligible in the study all participants had to meet the following criteria: (1) no participation in regular physical activity (i.e., no participation in structured group exercise or individual physical activity or sport as, for example, strength training, aerobics, yoga in the previous 5 years; (2) medically stable (3) able to transport themselves to the training facilities.

Measurements

Body composition

Lean body mass (LBM) was measured during fasting conditions by bioimpedance (arm to leg method). Prior to

the test, all subjects were asked to empty their bladder. The calculations were derived from the equations elaborated by Heitmann (1990) for elderly Danish people. This method has been cross-validated with elderly subjects against a four-compartment-model based on measurements of total body water (TBW) and potassium (TBK) with a reliability of body fat evaluated by linear regression analysis of $r = 0.94$ (Heitmann 1990).

Coupled eccentric–concentric and concentric-alone muscle contractions

Testing protocol Coupled eccentric–concentric and concentric-alone muscle contractions were assessed by means of a standardised countermovement jump (CMJ) and squatting jump (SQJ), respectively (Caserotti et al. 2001; Holsgaard et al. 2007). Jumping tests (CMJ and SQJ) were selected as these motor tasks reflect maximal performance under weight-bearing multi-joint conditions. It is believed that this provides significant functional information concerning the ability of aged individuals to produce maximal performance (i.e., maximal muscle power and jump height) during coordinated motor tasks when dealing with the biomechanical constraints dictated by the external force due to body weight. Both tests were performed on a force platform (Model 9281 B, Kistler, Switzerland), as described in detail previously (Caserotti et al. 2001). The CMJ started from a resting standing position, from which the subjects were instructed to perform a fast downward movement (to about 90° knee flexion) immediately followed by a fast upward movement while intending to jump as high as possible. Importantly, each subject was allowed to perform the downward movement to the depth and speed that they felt acceptable according to their individual capacity (e.g., eccentric/concentric muscle strength, balance control, flexibility). Therefore, individual differences in body configuration for ankle, knee and hip angles and trunk position may have occurred, despite instructions for knee flexion to about 90° were given. The displacement of the body center of mass was used to monitor the global changes in body configuration pre to post training and between the squatting and countermovement jumps (see "Force signal processing").

For the SQJ, the subjects were instructed to start from a static position of 90° at the knee angle. Prior to the jump the position was controlled with a manual goniometer. During the jumps, hands were kept on the hips. Following a 2-min rest, three maximal CMJ and three maximal SQJ were performed with 1-min interval between each test. The jumping test protocols were carefully explained and shown to each participant and emphasis on a rapid transition between the eccentric and concentric phases was given for the CMJ. Subsequently, subjects performed several submaximal trials to automate the technique. Tests were accepted for further analysis only when technique was considered acceptable. This was generally achieved with 2–3 submaximal trials. Furthermore, visual inspection of the vertical ground reaction force signal was performed in each jump to ensure that no undesired pre-movement took place.

The trial with maximal jump height (JH) calculated by the kinetic take-off impulse (explained below) of CMJ and SQJ, respectively, was selected for further analysis.

Force signal processing A kinetic profile of the CMJ and SQJ was investigated in the time domain by recording the vertical force signal (Fz) from the force platform at 1 kHz sampling rate by means of an external A/D converter (dt28ez Data Translation). The Fz signal was later analysed using customised analysis software according to the method of Caserotti et al. (2001). In brief, the vertical velocity of the body center of mass was obtained by time integration of the acceleration signal: Vertical velocity, $v = \int_0^t a(t)\mathrm{d}t = \int_0^t [F(t)/m - g]\mathrm{d}t$, in which a is the vertical acceleration of the center of mass, F is the vertical force measured directly by the platform, m is the body mass of the subject and g is the acceleration due to gravity (9.81 m s^{-2}).

This procedure allowed investigating two relevant features of these two multi-joint weight-bearing motor tasks: (1) maximal mechanical performance, identified as maximal jump height (JH) and peak and mean mechanical muscle power (P_{peak}, P_{mean}), and (2) provided a global description of the motor strategy with which the motor task is accomplished. The latter was obtained by identifying selected kinetic and temporal variables from the Fz signal integration procedure. In details, the countermovement jump was divided into two phases according to the center of mass velocity curve: (1) eccentric phase (Ep), i.e., the phase of downward movement of the center of mass (negative velocity) and (2) concentric phase (Cp), i.e., the phase of upward movement of the center of mass (positive velocity) (Caserotti et al. 2001). Leg extension mechanical power was continuously calculated throughout the concentric phase of the CMJ and SQJ movement as the instantaneous product of Fz force and vertical velocity and P_{mean} was then obtained. Further, since instantaneous mechanical power is determined by the product between force and velocity, maximal peak power can be increased (or decreased) by either increasing (or decreasing) the velocity or force at P_{peak} (V_{ppeak}, Fz_{ppeak}), respectively. In addition, concentric work (work), duration of concentric phase (T_{conc}) and center of mass displacement (ds$_{conc}$) were assessed during the SQJ and the Cp phase of the CMJ.

To determine changes in movement pattern during the eccentric phase (Ep) of the CMJ, the latter was subdivided into an acceleration phase (Ep_{acc}) and a deceleration phase (Ep_{dec}). Ep_{acc} was defined as the movement interval between onset of downward movement and the instant of maximal downward (negative) velocity. Ep_{dec} was defined as the interval between the instant of maximal downward velocity and the instant when the downward velocity reached zero (=end of downward movement) (Caserotti et al. 2001). Subsequently, the following kinetic parameters were identified: peak downward acceleration (a_{peak}) and minimum vertical force (Fz_{min}) for the Ep_{acc}, and peak deceleration (d_{peak}) and maximal vertical force (Fz_{max}) for the Ep_{dec}.

Variables for pre-stretch enhancement Pre-stretch enhancement of coupled eccentric-concentric (CMJ) versus concentric-alone (SQJ) muscle contraction mode was determined by analysing differences in JH, P_{peak} (maximal mechanical performance), mean power (P_{mean}), and velocity and force at P_{peak} (V_{ppeak}, Fz_{ppeak}), concentric work (work), duration of concentric phase (T_{conc}) and displacement of the center of mass (ds_{conc}). This comparison was carried out as pre-stretch enhancement of CMJ versus SQJ may be detectable as performance potentiation (increased JH and P_{peak}) and/or as differences in the kinetic and temporal variables selected for the analysis. Notably, even when direct performance potentiation cannot be detected (unchanged JH and P_{peak}), selected kinetic and temporal variables (e.g., work or P_{mean}) may still indicate pre-stretch enhancement effect.

Variables for training effect Training effects were monitored by analysing JH, P_{peak}, V_{ppeak}, and Fz_{ppeak}, P_{mean}, Work, ds_{conc} and T_{conc} for the concentric phase of the CMJ and the SQJ. In addition, a_{peak}, Fz_{min}, d_{peak}, Fz_{max} and the eccentric displacement of the body center of mass were analysed during the eccentric phase of the CMJ.

Good-to-excellent test–retest repeatability was recently reported from our laboratory in elderly subject for the various CMJ test parameters assessed as within-subjects coefficient of variation (CV_{w-s}) (Holsgaard et al. 2007). In particular, for selected CMJ variables the CV_{w-s} for P_{peak}, P_{mean}, JH were 2.9, 5.1 and 7.1%, respectively. Further, CV_{w-s} for V_{ppeak}, Fz_{ppeak}, work, and ds_{conc} were 2.9, 3.5, 6.8 and 8.4%, respectively (Holsgaard et al. 2007).

Functional motor performances

Functional motor performances were assessed as (1) a timed five-repeated chair rise test (Guralnik et al. 1994), (2)

timed 10-m walking test at maximal speed, (Vestergaard et al. 2006), (3) timed 30-m walking test at maximal speed, and (4) physical performance test (PPT, Reuben and Siu 1990). The latter assesses multiple domains of physical function and consists of seven items reflecting activities of everyday living (simulated eating, writing a sentence, turning 360°, putting on and removing a jacket, lifting a book, picking up a coin from the floor, a 50-foot walk test). All subjects were able to walk without walking aids.

Intervention programme

The training group (TG) participated in a 36-week multicomponent physical training programme, 60 min twice a week. A typical session included 10 min warm up followed by various exercise activities such as aerobics (i.e., walking, running), muscle strength (exercises using own body weight), endurance, postural control exercises, flexibility, and reaction exercises. The training program was designed to reflect a typical training session commonly offered in public and private settings for elderly people. The training intensity during the classes was controlled for the aerobic component and monitored by a pulse watch with four recordings per minute (Polar PE 4000, Finland). The aerobic training target was set above 65% of individual maximal heart rate for at least 30 min. Individual maximal heart rate was directly measured by a maximal oxygen uptake test performed on a bicycle ergometer and reported elsewhere (Puggaard 2003). The strength training stimuli was continuously increased in terms of repetitions and duration of each exercise and intensity (i.e., overloading) according to the subjects' capability. An example of training stimuli for lower limbs muscle strength is provided as following: half squat exercise using own body weight was initially proposed with few repetitions while holding on to a firm support. This was progressively increased throughout the 36-week training period by increasing (1) duration of the stimuli (i.e., number of repetitions) and (2) intensity by progressing to full squat (i.e., increasing the depth of the squat), to one leg half squat, one leg full squat, frontal and lateral lounge and with the use of elastic tubes as resistance. Similar progression in intensity was also applied for the other training components (e.g., balance).

The control group (CG) did not engage in any form of physical exercise training during the study period.

Statistical analysis

Results are expressed as mean and standard deviation. Differences between CMJ and SQJ, as well as pre-to-post

intervention differences within-groups were evaluated using Wilcoxon signed rank test for paired observations. Pre, post and intervention differences between groups were compared using Mann–Whitney test for unpaired observations. Correlation analysis was performed by the Spearman's Rho test. A probability level of 0.05 (two-tailed) was accepted for statistical significance.

Results

Anthropometric data are reported in Table 1. No significant changes were observed after the training period in any of the anthropometrical parameters. Correlation analysis showed no relationships between pre to post differences in body weight, fat free mass and fat mass and the pre to post differences in jump height and peak power for any of the subject groups (data not shown). Thirty-nine subjects (25 from CG and 14 from TG) completed the study. Drops out were unrelated to the study.

Coupled eccentric-concentric versus concentric muscle contraction: pre-stretch effect

Prior to training maximum power exertion and performance (P_{peak} and JH) were not enhanced in coupled eccentric–concentric (CMJ) compared to concentric-alone muscle contraction (SQJ, Table 2). Jump height and P_{peak} in the CMJ was 10.26 cm and 23.45 W kg^{-1} versus 10.41 cm and 23.12 W kg^{-1} in the SQJ, respectively. When P_{peak} was decomposed into its velocity (V_{ppeak}) and force (F_{ppeak}) components, F_{ppeak} differed 4% between CMJ and SQJ ($P < 0.05$) whereas no difference was found for V_{ppeak} (Table 2). Mean power (P_{mean}) was significantly higher during CMJ compared to SQJ, while work, displacement of center of mass during concentric phase (ds_{con}), and duration of the concentric phase (T_{con}) showed significant lower value in CMJ compared to SQJ (Table 2).

Changes with training

Within- and between-groups changes in mechanical jumping variables for the concentric phase of CMJ and SQJ expressed in percentage are displayed in Fig. 1 and for functional motor performances in mean and SD values in Fig. 2.

Countermovement jump

CMJ JH increased in TG while decreasing in CG (from 9.68 ± 3 to 10.82 ± 3.3 and from 10.59 ± 3.6 to 9.9 ± 3.8 cm, respectively; $P < 0.05$). Similarly, P_{peak} increased in TG from 22.8 ± 3.2 to 24.1 ± 3.7 W kg^{-1} while decreasing in CG from 23.8 ± 4.1 to 23.0 ± 4.5 ($P < 0.05$). A significant between-groups delta (Δ) change was observed for JH and P_{peak} ($P < 0.05$, Fig. 1). When P_{peak} was decomposed into F_{ppeak} and V_{ppeak}, V_{ppeak} increased in TG from 1.48 to 1.54 m s^{-1} ($P < 0.05$) while decreasing in CG from 1.55 to 1.49 m s^{-1} ($P < 0.05$). F_{ppeak} remained unchanged for both groups after the training period (TG from 15.6 ± 1.5 to 15.6 ± 1.5 N kg^{-1}; CG from 15.4 ± 1.2 to 15.5 ± 1.4 N kg^{-1}). CMJ P_{mean} increased significantly in TG after the period of training from 12.7 ± 2.1 to 13.6 ± 2.3 W kg^{-1}, whereas no changes were observed for CG (12.7 ± 2.8 W kg^{-1}; 12.9 ± 2.7 W kg^{-1}). No changes occurred for TG subjects in work, duration of concentric phase (T_{con}) and displacement of the body center of mass (dS_{conc}), (pre to post: from 4.0 ± 0.9 to 4.1 ± 0.7 J kg^{-1}, from 315 ± 53 to 305 ± 43 ms and from 31.1 ± 7.0 to 31.5 ± 4.5 cm, respectively). Conversely, CG decreased significantly in all three variables (pre to post: from 4.3 ± 0.8 to 4.1 ± 0.8 J kg^{-1}, from 356 ± 99 to 321 ± 71 ms and from 33.9 ± 5.7 to 31.6 ± 6.0 cm, respectively) ($P < 0.05$). Fz_{mean} remained unaltered in both groups (TG from 12.8 ± 0.7 to 13.1 ± 0.8 N kg^{-1} and CG from 12.8 ± 0.9 to 12.8 ± 1.1 N kg^{-1}).

No changes in mechanical variables during the CMJ eccentric phase (ds_{ecc}, Fz_{min}, a_{peak}, Fz_{max}, d_{peak}) were observed in TG (Table 3). In contrast, CG showed a

Table 1 Anthropometric characteristics of the subjects, pre and post intervention

	Training group ($n = 14$)			Control group ($n = 25$)		
	Pre	Post	Δ (%)	Pre	Post	Δ (%)
Body mass (kg)	80.0 ± 11.2	77.7 ± 11.9	-2.9	81.9 ± 10.9	82.5 ± 11.5	0.7
Height (cm)	171.6 ± 4.2	172.0 ± 4.1	0.2	172.5 ± 5.9	172.5 ± 6.0	0
Body fat (%)	30.5 ± 3.9	29.3 ± 5.2	-3.9	31.4 ± 5.0	32.4 ± 4.7	3.2
Lean body mass (%)	69.5 ± 11.2	70.7 ± 11.9	1.7	68.6 ± 10.9	67.6 ± 11.5	-1.5

Values are given as the means $\pm$ SD. Δ values are expressed as pre- post-intervention in percent

Table 2 Mechanical muscle variables during pre-stretch (coupled eccentric-concentric-CMJ) and without pre-stretch (concentric-alone-SQJ) muscle contraction modes at baseline

	JH (cm)	P_{peak} (W kg^{-1})	F_{ppeak} (N kg^{-1})	V_{ppeak} m s^{-1}	P_{mean} (W kg^{-1})	$V_{takeoff}$ (m s^{-1})	T_{conc} (m s^{-1})	Work (J kg^{-1})	ds_{con} (cm)
CMJ	10.3 ± 3.4	23.5 ± 3.8	15.5 ± 1.3	1.52 ± 0.2	12.7 ± 2.5	1.40 ± 0.2	341.3 ± 89.8	4.2 ± 0.8	31.5 ± 5.4
SQJ	10.4 ± 4.0	23.1 ± 4.5	15.0 ± 1.2*	1.54 ± 0.2	10.0 ± 1.9*	1.40 ± 0.3	468.3 ± 86.9*	4.6 ± 0.9*	37.0 ± 6.3*

CMJ Countermovement jump concentric phase; *SQJ* squatting jump; *JH* jump height; P_{peak} peak power; F_{ppeak} force at peak power; V_{ppeak} velocity at peak power; P_{mean} mean power; $V_{takeoff}$ take-off velocity; T_{conc} duration concentric phase; *Work* concentric mechanical work; ds_{con} displacement of center of mass during concentric phase

* Significant difference between squatting and countermovement jump, $P < 0.05$

Fig. 1 Within-group development in percentage (post/pre 100–100) following training during the squatting jump and countermovement jump concentric phase; *JH* jump height, P_{peak} peak power, F_{ppeak} force at peak power, V_{ppeak} velocity at peak power, P_{mean} mean power, *work* mechanical work during the concentric phase, T_{con} duration of concentric phase, dS_{con} displacement of body center of mass during the concentric phase, dS_{ecc} displacement of body center of mass during the eccentric phase, Fz_{mean} mean vertical force. *Significant within-group differences $P < 0.05$, † significant between-group differences, $P < 0.05$
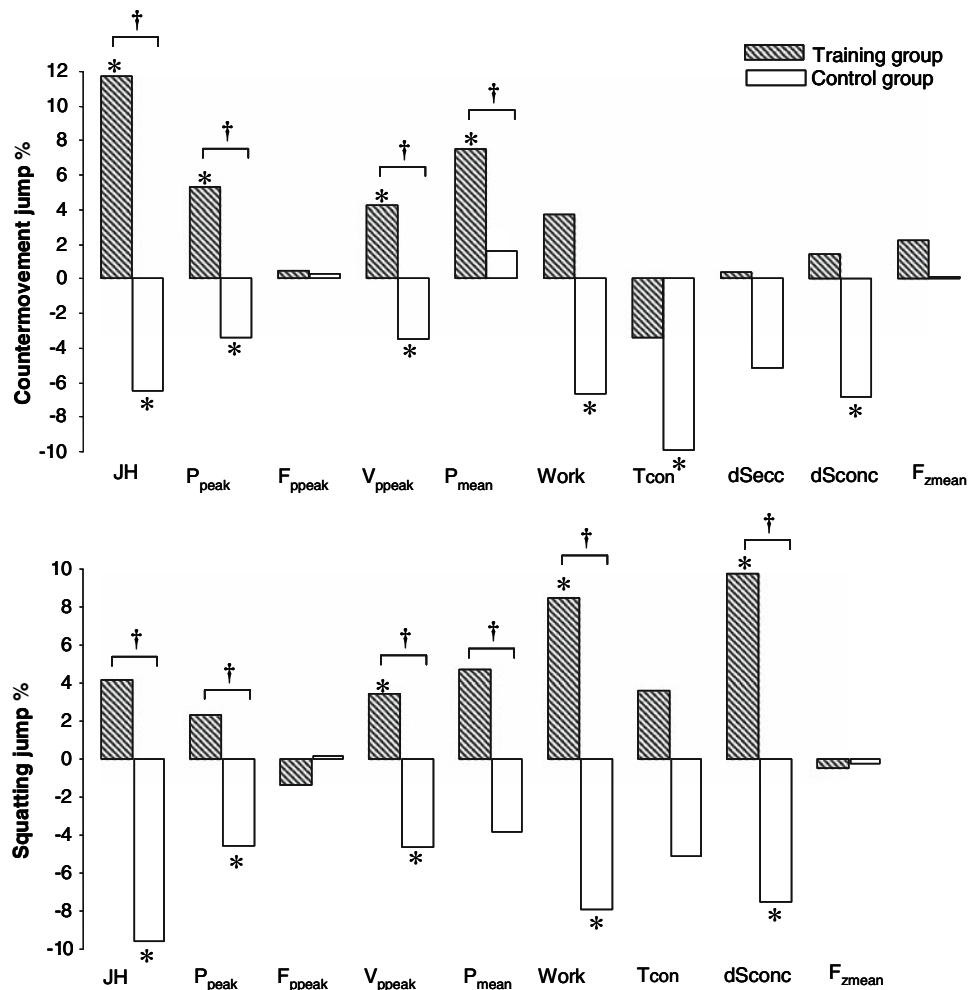

significant increase in Fz$_{max}$ and d_{peak} following the 36-week period (Table 3). For both groups duration of the eccentric acceleration and deceleration phases of the CMJ remained unchanged during the intervention period (data not shown).

Squatting jump

CG showed a decrease in JH (from 10.8 ± 4.5 to 9.8 ± 4.2 cm), P_{peak} (from 23.6 ± 5.0 to 22.5 ± 5.1 W kg^{-1}) and V_{ppeak} (from 1.56 ± 0.2 to 1.49 ± 0.2 m s^{-1}, $P < 0.05$; Fig. 1). The only variable that explained the decrease in JH and P_{peak} was a decrease in V_{ppeak} since F_{ppeak} remained unchanged (from 15.0 ± 1.2 to 15.0 ± 1.5 N kg^{-1}). Conversely, no changes were found for TG group in JH (from 9.7 ± 3.0 to 10.1 ± 3.2 cm), P_{peak} (from 22.3 ± 3.5 to 22.9 ± 3.4 W kg^{-1}) and F_{ppeak} (from 14.9 ± 1.1 to 14.7 ± 0.9 N kg^{-1}), whereas V_{ppeak} increased significantly, from 1.50 ± 0.2 to 1.55 ± 0.2 m s^{-1} (Fig. 1). Significant between-groups Δ changes

Fig. 2 Pre to post intervention period changes in functional motor performances. TG training group CG control group. Values are given in mean and SD. * Significant within-group differences $P < 0.05$; † significant between-group differences, $P < 0.05$
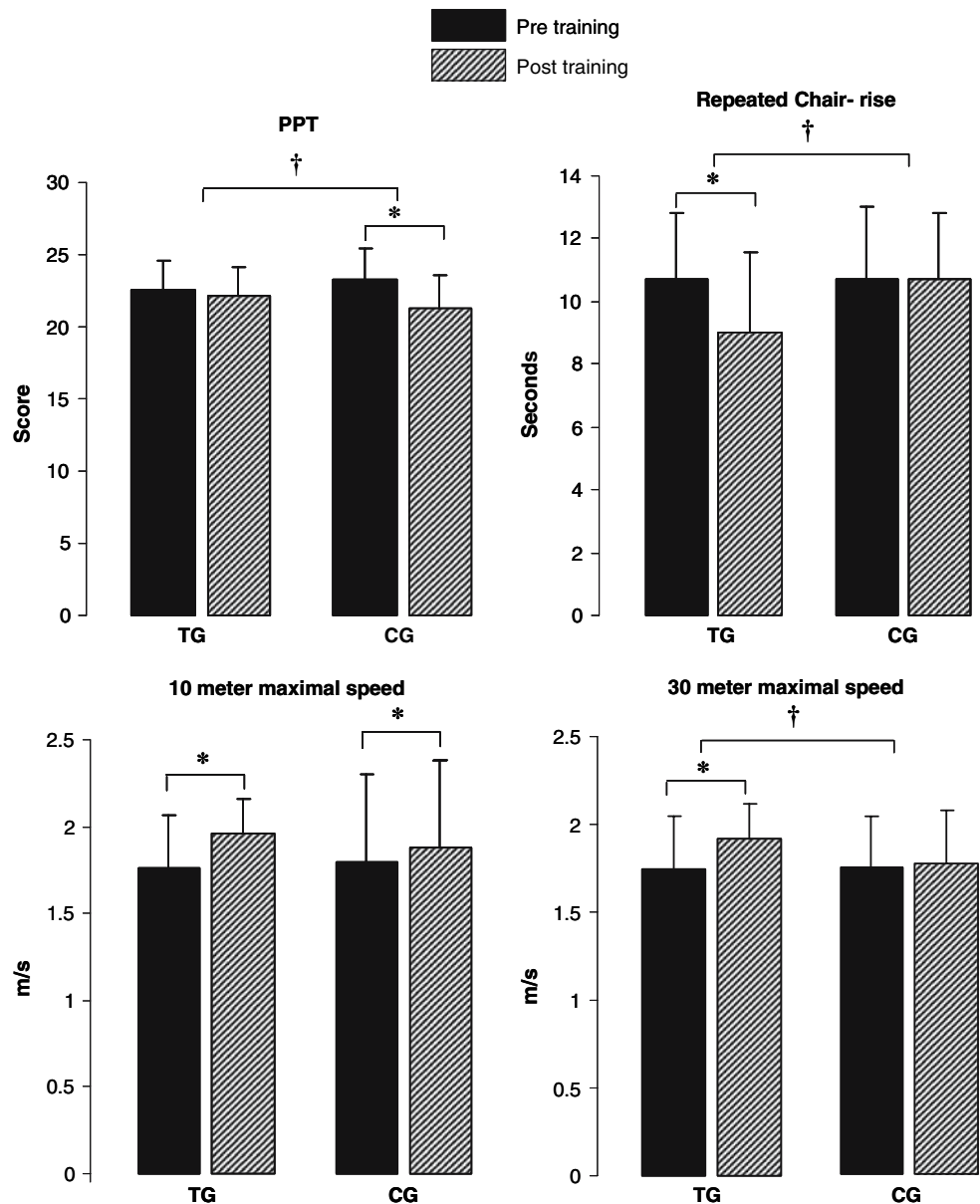
Table 3 Eccentric acceleration and deceleration phases of a countermovement jump

	ds_{ecc} (cm)	Acceleration phase		Deceleration phase	
		a_{peak} (m s^{-2})	Fz_{min} (N kg^{-1})	d_{peak} (m s^{-2})	Fz_{max} (N kg^{-1})
TG pre	22.0 ± 6.6	5.2 ± 2.1	4.6 ± 2.1	7.0 ± 3.0	16.8 ± 3.0
TG post	22.1 ± 5.2	5.5 ± 2.1	4.3 ± 2.1	7.6 ± 2.4	17.4 ± 2.4
CG pre	24.3 ± 5.6	4.9 ± 1.5	4.9 ± 1.5	6.1 ± 2.0	15.9 ± 2.0
CG post	23.0 ± 5.5	4.7 ± 1.4	5.1 ± 1.4	7.0 ± 2.1*	16.9 ± 2.1*

TG and *CG* training group and control group, respectively pre and post intervention; ds_{ecc} displacement of the body center of mass during eccentric phase; a_{peak} peak acceleration; Fz_{min} minimal vertical force; d_{peak} peak deceleration, Fz_{max} maximal vertical force.

*Significant within-group differences, $P < 0.05$

were observed for JH and P_{peak}, V_{ppeak} (Fig. 1). P_{mean}, duration of concentric phase and Fz_{mean} remained unchanged in the TG (pre to post: from 9.7 ± 1.5 to 10.2 ± 1.7 W kg^{-1}, from 12.9 ± 0.8 to 12.8 ± 0.7 N kg^{-1} and from 452 ± 73 to 468 ± 63 ms, respectively) and in CG (pre to post: from 10.2 ± 2.1 to 9.8 ± 1.9 W kg^{-1},

from 12.9 ± 0.8 to 12.8 ± 0.9 N kg^{-1}, and from 477 ± 94 to 453 ± 66 m s, respectively). A significant increase was reported for displacement of the body center of mass and work in TG (pre to post: from 34.9 ± 5.3 to 38.2 ± 5.7 cm and from 4.4 ± 0.7 to 4.7 ± 0.7 J kg^{-1}, respectively), whereas CG exhibited a significant decrease (pre to post: from 38.1 ± 6.6 to 35.3 ± 6.3 cm and from 4.8 ± 1.0 to 4.4 ± 0.9 J kg^{-1}, respectively). Significant between-groups Δ changes were observed for P_{mean}, work and concentric displacement of the body center of mass (Fig. 1).

No sign of performance enhancement (i.e., elevated JH, P_{peak}) was found in CMJ compared to SQJ either before or after the training period in both groups (data not shown).

Functional motor performances

Performance in chair rise test, 10- and 30-m maximal walking speed improved significantly in TG after training (pre to post: from 10.7 ± 2.1 to 9.0 ± 2.6 s, from 1.76 ± 0.3 to 1.96 ± 0.2 m s^{-1} and from 1.75 ± 0.3 to 1.92 ± 0.2 ms^{-1}, respectively), while PPT remained unaltered (from 22.6 ± 2.0 to 22.2 ± 1.9, Fig. 2). Conversely, PPT significantly decreased in CG (from 23.3 ± 2.2 to 21.3 ± 2.3) whereas 30-m maximal walking speed and repeated chair rise remained unaltered (from 1.74 ± 0.3 to 1.77 ± 0.3 m s^{-1} and from 10.7 ± 2.1 to 10.7 ± 2.3 s, Fig. 2). Ten-meter maximal walking speed significantly increased in CG after the intervention period from 1.80 ± 0.5 to 1.88 ± 0.5 m s^{-1}. Significant between-groups Δ changes were observed for PPT, repeated chair rise and 30-m walking speed (Fig. 2).

Discussion

The major findings of this study were that (1) pre-stretch enhancement during coupled eccentric–concentric contraction (CMJ) did not improve performance (i.e., no enhanced maximal muscle power and jump height) compared with concentric muscle contraction (SQJ). Nevertheless, pre-stretch enhancement occurred as for a similar SQJ and CMJ maximal performance, elderly people during CMJ employed lower mechanical work, higher mean muscle power, shorter concentric phase duration and shorter displacement of body center of mass; (2) 36-week multicomponent training resulted in increased jump performance (JH) and elevated maximal muscle power output (P_{peak}) during CMJ. Contrarily, untrained controls exhibited a decline in maximal jump performance and power output both during the CMJ and SQJ; (3) kinetic and temporal profile of the eccentric and concentric phase of the CMJ and SQJ changed in the control group, indicating a

potential deterioration of movement pattern after the intervention period; (4) multicomponent training was able to counteract the decline observed in PPT in the CG and produce improvement in maximal walking speed and repeated chair-rise in TG.

Coupled eccentric-concentric versus concentric muscle contraction

Generally, in young subjects CMJ jump height and P_{peak} is reported to exceed SQJ by 7–20% (Bosco and Komi 1980; Bobbert et al. 1996; De Vito et al. 1998; Izquierdo et al. 1999b; Paasuke et al. 2003). In the present study, no direct performance enhancement was observed with the countermovement jump compared to the squatting jump as indicated by similar jump heights and P_{peak} (Table 2). This finding is in agreement with previous reports that implemented jumping assessment in the elderly (Bosco and Komi 1980; De Vito et al. 1998; Paasuke et al. 2003). Bosco and Komi (1980) showed a progressive age-related decrease in performance enhancement from mid-20s until the age of 70 years. Similarly, Izquierdo et al. (1999a) observed performance potentiation (enhanced JH) in CMJ versus SQJ, in subjects 40 years old, while no enhanced performance was observed in the oldest group (70 years). This was further confirmed in elderly women (52–58 and 66–77 years) compared to the young women (20–23 years, Paasuke et al. 2003). In contrast, other studies have reported an intact age related pre-stretch enhancement in a coupled eccentric–concentric compared to a concentric-alone muscle action using isokinetic muscle assessment (Svantesson and Grimby 1995; Lindle et al. 1997). The present study demonstrated pre-stretch enhancement during CMJ compared to SQJ for some but not all mechanical variables. This was detected by the analysis of the kinetic and temporal profile of the center of mass during jumping. During the concentric phase of the CMJ, compared with the SQJ, elderly subjects had (1) lower displacement of the body center of mass (6.5 cm), (2) shorter concentric phase (127 ms), (3) lower mechanical work (0.4 J kg^{-1}) and (4) higher mean power (27%). This occurred despite similar maximal performance (i.e., jump height and peak power) was obtained for both jumps (Table 2). Thus, although no direct maximal performance potentiation was observed, the present data indicate that during coupled eccentric–concentric contraction elderly people maintain the ability to have enhanced mechanical muscle output compared to concentric contraction alone. Importantly, in the CMJ pre-stretch condition the elderly produced the same maximal mechanical output using about 120 ms less.

Several mechanisms such as elastic energy recoil (Bosco and Komi 1980), enhanced muscle mechanics (Bobbert

et al. 1996) and involvement of the stretch-reflex pathway (Bosco and Viitasalo 1982; Komi 2000) have been proposed for pre-stretch enhancement in young adults during a CMJ compared to SQJ. Morphological and functional age-related changes in the passive and active elements of the muscle–tendon complex (Magnusson et al. 2003) along with reduced feedback gain in the stretch–reflex pathways (Chalmers and Knutzen 2000) may possibly contribute to the reduced or absent pre-stretch enhancement in CMJ.

Changes induced by training

Two relevant findings were observed after the training period in both study groups; firstly a substantial decline in maximal performance and mechanical muscle output (JH and P_{peak}) was observed for the control group during the 36-week study period; secondly, multicomponent training effectively counteracted this age-related decline in maximal performance.

After the intervention period the control group showed a significant decrease in P_{peak} of 4.5 and 3.4% during SQJ and CMJ, respectively. Both changes were predominantly due to a reduction in V_{ppeak}. This decrease observed in CG is in agreement with previous findings where an age-related decline in peak power of 3.5% per year was observed (Skelton et al. 1994). Maximum jump height exhibited even a larger decline (7–9%). For both jumps a change in the center of mass downward displacement was observed (Fig. 1) which was accompanied by a reduced mechanical work and phase duration (only in the CMJ, Fig. 1). Nevertheless, no changes in mean power occurred for the two jumps. Although only speculative, this finding can be interpreted as the inability for the control subjects to tolerate a deeper downward displacement of the body center of mass, which potentially would determine a higher peak force (Fz_{max} during the CMJ) and/or to initiate the movement from a more disadvantaged joint position.

Multicomponent training led to increased P_{peak} and JH during CMJ in TG, while these parameters decreased over the 8-month study period in the untrained age-matched controls. Furthermore, the multicomponent training fully abolished the decrease in these parameters seen in the untrained controls during SQJ.

These results are in agreement with a previous study (De Vito et al. 1999) where 12 weeks of low intensity conditioning exercise led to changes in CMJ peak power that were accompanied by relative increase in velocity at peak power along with unaltered force at peak power. In the present study, despite no significant changes were observed for the TG in displacement, work, phase duration and mean force during the concentric phase of the CMJ, increases in mean power were observed after training. Contrarily to the control group, the kinetic profile of the CMJ eccentric phase (duration of phases, forces, acceleration, displacement) did not show any significant change in the training group (TG) following training (neither in the acceleration nor deceleration phases, Table 3; Fig.1). This indicates that the motor pattern was retained in TG but not in CG pre and post intervention period for the eccentric and concentric phase of CMJ. Additionally, changes in center of mass displacement and mechanical work were observed for the trained subjects during the SQJ (Fig. 1). Thus, despite SQJ knee position was controlled manually with a goniometer the training group was able to attain a longer range of excursion of the body center of mass following training hence allowing the body center of mass to travel a longer distance and thereby produce more work. This may have occurred for a longer range of excursion of the ankle during the ankle push-off phase. Despite this, changes in maximal performance remain unaltered (JH and P_{peak}) although a trend for increase emerged ($P = 0.07–0.09$).

Importantly, this training program was able to prevent the decline observed in CG in the PPT test. This is highly relevant as PPT test includes items, which reflect basic, and more advanced everyday activities and provide a global assessment of balance, mobility, coordination fine and gross motor function. In addition, improvements in the training subjects were observed for repeated chair-rise, 10- and 30-m maximal walking tests. Thus, this training type was able to maintain and even elicit improvements in selected functional motor performances in the training subjects (Fig. 2).

The present changes with the multicomponent training may have occurred due to increased neural activation and/or due to muscle hypertrophy. However, the training type was of relatively low intensity and despite the long duration (36 weeks) muscle growth may have been limited. In addition, potential interference for muscle power and explosive force increases may have occurred due the combined strength and aerobic training stimuli (Häkkinen et al. 2003). Nevertheless, despite this potential interference, the multicomponent training designed for this study was able to counteract the age-related changes in maximal mechanical muscle performance (JH and peak power) and in selected functional motor performances observed in the control subjects and to induce positive adaptation in the training subjects.

In summary, despite that no direct performance potentiation was observed in the elderly for coupled eccentric–concentric (CMJ) versus concentric-alone (SQJ) muscle contraction (JH, P_{peak}) signs of pre-stretch enhancement were revealed by the reduced center of mass displacement, mechanical work, shorter concentric phase duration and higher mean muscle power during the CMJ. This occurred despite maximal mechanical performance was achieved for

both jumps. Multicomponent physical training programme appeared to counteract the age-related decline in maximal performance and the altered motor pattern observed in the control subjects as identified by specific kinetic and temporal variables (e.g., Fz_{max}, d_{peak}). In addition, significant increases in maximal muscle performance were observed in the trained subjects (JH and P_{peak}). Finally, this training type was able to maintain and even elicit improvements in selected functional motor performances in the training subjects.

In conclusion, multicomponent training twice a week which is commonly used for training in the elderly was well-tolerated and effectively counteracted the age-related decline observed in the control untrained subjects while inducing significant increases in neuromuscular function in the trained elderly.

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