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ORIGINAL ARTICLE

Effects of strength, endurance and combined training on muscle strength, walking speed and dynamic balance in aging men

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Abstract The aim of this study was to examine effects of 21-week twice weekly strength (ST), endurance (ET) and combined (ST + ET 2 + 2 times a week) (SET) training on neuromuscular, endurance and walking performances as well as balance. 108 healthy men (56.3 ± 9.9 years) were divided into three training (ST; $n = 30$, ET; $n = 26$, SET; $n = 31$) groups and controls (C $n = 21$). Dynamic 1RM and explosive leg presses (1RMleg, 50%1RMleg), peak oxygen uptake using a bicycle ergometer ($VO_{2\mathrm{peak}}$), 10 m loaded walking time (10WALK) and dynamic balance distance (DYND) were measured. Significant increases were observed in maximal 1RMleg of 21% in ST ($p < 0.001$) and 22% in SET ($p < 0.001$) and in explosive 50%1RMleg of 7.5% in ST ($p = 0.005$) and 10.2% in SET ($p < 0.001$). $VO_{2\mathrm{peak}}$ increased by 12.5% in ET ($p = 0.001$) and 9.8% in SET ($p < 0.001$). Significant decreases occurred in 10WALK in ST ($p < 0.001$) and SET ($p = 0.003$) and also in DYND of −10.3% in ST ($p = 0.002$) and −8% in SET ($p = 0.028$). The changes in C remained minor in all variables. In conclusion, ST and SET training produced significant improvements in maximal and explosive strength, walking speed and balance without any interference effect in SET. Significant but moderate relationships were observed between strength and dynamic balance and walking speed, while no corresponding correlations were found in the ET group.

Keywords Combined strength and endurance training · Balance · Functional capacity · Aging men

Introduction

The ability of aging humans to perform activities of daily life is strongly related to maintenance of the main elements of health-related physical fitness (i.e. aerobic capacity, strength production, balance and mobility) (Stathokostas et al. 2004; Fleg et al. 2005; Faulkner et al. 2007). For example, walking speed, balance and aging workers' ability to cope with their work, especially in physically demanding occupations, and in the prevention of falls are associated not only with maximal muscle strength and aerobic capacity but also with explosive strength production of the leg extensors (Ilmarinen 1992; Landers et al. 2001; Rantanen 2003; Runge and Hunter 2006; Schrack et al. 2010).

Several studies have reported aging-related declines in locomotor function including decreases in maximal strength of 30–50% (Häkkinen 1994; Jozsi et al. 1999) and in maximal oxygen uptake ($VO_{2\max}$) as much as 60% (Astrand et al. 1973; Fleg et al. 2005; Hollenberg et al. 2006) between the ages of 30 and 70 years. Similar declines occur during aging also in visual, somatosensory

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(Whipple et al. 1993; Lord 2006), vestibular (Matheson et al. 1999) and neurological biological systems (Horak 2006; Jiménez-Jiménez et al. 2011). These problems cause postural instability and possible problems with the balance (Era et al. 2006; Horak 2006; Lord 2006). Recent research on the total functions of the biological locomotor system affecting balance control is, however, still inadequate, and does not detail the multiple factors that induce the postural instability (Horak 2006; Runge and Hunter 2006). Furthermore, there are several independent risk factors for locomotor non-syncopal falls among aging humans. The most important risk factors include muscle strength of the knee and hip extensors and flexors and lateral postural stability (Horak 2006; Runge and Hunter 2006; Orr et al. 2008). Nevertheless, it is possible to slow down age-related decreases in neuromuscular function and aerobic capacity by performing strength- and endurance training using proper volume and intensity (Häkkinen 1994; Kasch et al. 1995; Häkkinen et al. 1998; Mian et al. 2007; Baker et al. 2007). Furthermore, increased maximal and explosive muscle strength has indirect effects on improved postural control and, thereafter, balance due to possible changes in explosive strength characteristics (Baker et al. 2007; Mian et al. 2007; Orr et al. 2008).

Training for aerobic capacity and muscle strength simultaneously may cause a negative interference effect in young participants in terms of the development of maximal and explosive muscle strength characteristics. This interference phenomenon may occur, especially if the volume, intensity and frequency of combined strength and endurance training are too high. Therefore, concurrent training, including running and free weight training may, in some cases, cause increases in maximal and explosive strength and power that are only of a low magnitude or a plateau may even be reached already after a relative short period (7–12 weeks) of training (Hickson 1980; Dudley and Djamilj 1985; Kraemer et al. 1995; Bell et al. 2000). On the other hand, several studies have reported no negative interference effect on maximal and explosive strength development in young or older participants under certain conditions. No negative interference effects on strength characteristics have been observed when the volume, intensity and frequency of combined strength and endurance training are low or moderate and, especially when endurance training have been performed on a stationary bicycle ergometer (Wood et al. 2001; Chtara et al. 2005; Izquierdo et al. 2005; Karavirta et al. 2009; Sillanpää et al. 2009). In addition, to the best of our knowledge, only a few studies such as Buchner et al. (1997) have examined the effects of prolonged combined strength and endurance training on strength development and balance in older participants observing interference effect in knee extension strength development that was lower compared to that of the strength training group only. The study protocol by Buchner et al. (1997) contained a training frequency of 6 times a week for the combined strength and endurance training. Nevertheless, no improvements were observed in practical field type balance tests.

Endurance training activates mostly slower motor units (type I muscle fibers) while strength training primarily activates faster motor units (type II muscle fibers). Therefore, endurance training may inhibit increases in strength characteristics, especially in the muscle fibers that are recruited during combined strength and endurance training (Hickson 1980; Kraemer et al. 1995; Bell et al. 2000). Surface electromyography has been commonly used as an indirect method to study neural changes during strength training (Moritani and Devries 1980; Häkkinen 1994; Häkkinen et al. 1998, 2001) and may also provide information on possible neural interference effects of combined strength and endurance (Häkkinen et al. 2003).

The purpose of this study was to examine effects of strength, endurance, and combined strength and endurance training on isometric and dynamic muscle strength, walking performance and balance capability in aging men. Strength training was performed utilizing a program that was planned not only for maximal strength development but also included leg extensor exercises of an explosive nature. We hypothesized that the present combined moderate frequency strength and endurance training, lasting for 21 weeks, would not lead to interference effects and, therefore, increases would occur in both strength characteristics and endurance capacity as well as in walking speed and dynamic balance in aging men.

Methods

Participants

All participants (130 men) were recruited from the city of Jyväskylä and the surrounding area through newspaper advertisements and by sending flyers by post and email. Telephone interviews were conducted by the examiner, including questions regarding medical history, occupational commitments, and current physical activity level. Selection to an examination by a physician was based on completed entry forms and interviews by the examiner. Participants with no contraindications to exercise (ACSM 2000), for example, known cardiovascular, pulmonary or musculoskeletal diseases and medications known to influence cardiovascular performance or muscle functions, were invited to clinical examination ($n = 125$). The 12-lead resting electrocardiogram (ECG) was recorded and the results were analyzed by a cardiologist who also screened all study participants for any medical conditions that would compromise the participant's successful participation in the study (e.g., orthopedic, endocrine, neurological medical disorders). The participants who passed the medical examination ($n = 120$) performed a maximal bicycle ergometer exercise test to voluntary exhaustion with ECG monitoring under the supervision of a physician. Men without evidence of cardiovascular diseases, musculoskeletal problems or other severe diseases proceeded to the training and testing period ($n = 117$). These participants were considered healthy. They were physically active, but had no background in systematic strength or endurance training.

The participants were informed about the design of the study as well as possible risks and discomforts related to the measurements and participation of the study after which they signed an informed consent. All study participants were informed of the independent possibility to stop measurements and participation of the study whenever they felt it was necessary. The Ethics Committee of the University of Jyväskylä, Jyväskylä, Finland approved the procedures of the present study.

Dropouts during the first medical testing period consisted of three participants due to personal health reasons (high blood pressure, coronary diseases). 114 men were randomized into four groups: strength training (ST $n = 31$), endurance training (ET $n = 26$), combined strength and endurance training (SET $n = 33$) and control (C $n = 24$). Dropouts during the training period consisted of one participant in the ST group and two participants in the SET group due to personal health reasons (lower back pain, chest pain and sprained ankle) and three participants in the control group due to other personal reasons (busy time schedules at work that caused lack of motivation). Therefore, the final number of participants included in the analysis was 108. Participants' characteristics are presented in Table 1

Experimental design

The participants were tested with the similar test protocols at weeks −2, 0, 10.5 and 21 during the 21-week training study. The participants were carefully familiarized and instructed in the correct performance technique of voluntary strength production of the leg muscles as well as functional- and balance tests during the first laboratory visit before the actual measurements started at week 0. The participants were also strongly encouraged during the actual measurements to make sure that their performance was correct and maximal. During the 21-week training period, both strength and endurance groups trained two times a week, and the combined strength and endurance group trained two times a week for strength and two times a week for endurance in order to study possible interference effects. All group (of 10–12 participants) training sessions were supervised by 1–2 MSc students specialized in the major of science of sport coaching and fitness testing. The participants in the control group were instructed to continue their habitual physical activities as before.

Training protocol

Endurance training

The intensity of endurance training performed on a bicycle ergometer was progressively increased and was based on aerobic performance tests (aerobic and anaerobic threshold) (Häkkinen et al. 2003). The thresholds for endurance training were determined based on respiratory parameters and blood lactate concentrations, as described in detail previously (Aunola and Rusko 1984). Heart rate monitoring was used during the training period, which was divided into three cycles of 7 weeks in duration. During the first training cycle, the participants trained for 30 min under the level of their aerobic threshold in both weekly sessions. Between weeks 5–7 every other training session included 10 min under the level of their aerobic threshold, 10 min between aerobic and anaerobic thresholds and 10 min under the level of their aerobic threshold in order to familiarize participants with higher intensity training. The other of the two weekly training sessions included 30 min of cycling under the level of their aerobic threshold. During the second training cycle, the 45-min session was divided into four loading intervals: 15 min under the level of the aerobic threshold, 10 min between the aerobic–anaerobic thresholds, 5 min above the anaerobic threshold, and 15 min again under the aerobic threshold. The other of the two weekly training sessions was 60 min under the aerobic threshold. The focus of training during the third 7-week cycle was to improve cycling speed and maximal endurance in a 60-min session: 30 min under

Table 1 Mean ± SD values of age, height, weight and body mass index (BMI) of subjects at 0 weeks

Group (n) at 0 weeks	Age (years)	Height (cm)	Weight (kg)	BMI
Strength (30)	56.5 ± 7.6	178.1 ± 6.2	83.9 ± 10.1	26.5 ± 3.0
Endurance (26)	55.5 ± 8.7	176.2 ± 6.1	79.2 ± 10.2	25.5 ± 3.3
Combined (31)	56.9 ± 7.5	177.0 ± 8.0	82.8 ± 12.9	26.3 ± 3.2
Control (21)	56.7 ± 9.9	175.3 ± 6.5	77.5 ± 10.4	25.1 ± 2.2
Strength + combined (61)	56.7 ± 7.5	177.6 ± 7.1	83.4 ± 11.5	26.4 ± 3.1

the aerobic threshold during the whole session altogether, 2 × 10 min between the aerobic anaerobic thresholds, and 2 × 5 min above the anaerobic threshold. Every other training session included 90 min of cycling at a steady pace under the aerobic threshold (Häkkinen et al. 2003; Holviala et al. 2010).

Strength training

The present 21-week training program was a total body program using machine exercises for the lower and upper extremities and trunk. Each training session included two exercises for the leg extensor muscles (bilateral leg press and knee extension), one exercise for the knee flexors (bilateral or unilateral knee flexion) and four to five other exercises for the other main muscle groups of the body (bench press, triceps pushdown, or lateral pull-down exercise for the upper body; sit-up exercise for the trunk flexors or another exercise for the trunk extensors; and bilateral/unilateral elbow flexion exercise or leg adduction/abduction exercise). Both the overall intensity and volume of training increased progressively throughout the training period following a periodized training program. The supervised training sessions averaged from 60 to 90 min in length (Holviala et al. 2010). The training period consisted of three training cycles of 7 weeks in duration: (1) to improve muscle strength endurance, (2) to produce muscle hypertrophy to increase overall muscle mass and (3) to optimize gains in maximal strength of trained muscles (Häkkinen et al. 1998). The individual loads for strength training were determined on the basis of the initial strength tests. Muscle strength exercises used during the first cycle of the training were carried out with light loads [40–60% of the one repetition maximum (1RM)] but with a high number of repetitions and multiple sets. To optimize muscle mass development during the second cycle, the loads increased progressively up to 60–80% of 1RM with a relatively short recovery time to produce muscle growth (Kraemer et al. 1990). The third cycle included somewhat higher loads (70–85% of the 1RM) to optimize strength gains.

Combined strength and endurance training

The combined training group performed two strength sessions and two endurance sessions a week on separate days. The strength and endurance sessions followed the protocols described above (Holviala et al. 2010).

Maximal isometric and dynamic strength, explosive power and EMG measurements

Dynamic maximal muscle strength and explosive muscle power were measured by the bilateral 1RM (1RMleg) and 50% load of 1RM (50%1RMleg) leg presses using a dynamometer (a modified David 210 horizontal leg press) (Häkkinen et al. 1998). The participants were in a seated position so that the hip angle was 110° and the starting knee angle was set to 70° with a manual goniometer. On verbal command, the participant performed a concentric leg and hip extension starting from the flexed position of 70° to the full extension of 180° against the resistance determined by the loads [kg] chosen on the weight stack. After each repetition, the load was increased (precision of 2.5 kg) until the participant was unable to extend the legs to the required position. The last acceptable extension with the highest possible load was determined as 1RM as used earlier by Häkkinen et al. (1998). Thereafter, the 50% leg press was measured using the load of 50% of the maximal 1RM result. The 50%1RMleg and hip extension power signal was averaged during the whole range of motion and calculated in watts (W).

During dynamic 1RM and 50% explosive leg and hip extensions EMG was measured from quadriceps muscles, (a) vastus lateralis (VL), (b) vastus medialis (VM) and (c) rectus femoris (RF). Bipolar surface EMG recording (miniature-sized skin electrodes ECG-MedOla, Oriola Inc., Espoo, Finland inter-electrode distance 20 mm, input impedance <10 KΩ, rejection rate 80 dB, 1,000 gain) was employed. Seniam (2004) guidelines were followed for skin preparation, electrode placement and orientation and placing of the electrodes. Small tattoos on the skin were used to ensure the same electrode placement at both 0 and 21 week time points. Raw EMG signals passed from the transportable pack, around participants' waist, to the receiving box (Telemyo 2 400R, Noraxon, Scottsdale, AZ, USA), and then relayed to the computer via an AD converter (Micro 1401, CED, Cambridge, UK). EMG signals were filtered using a band-pass filter (20–350 Hz) before the analysis. During dynamic 1RMleg press EMG signals were averaged for the concentric contraction. Maximum iEMG during the isometric action was determined from the time period of 500–1,500 ms. The best attempts during the measurements with regard to maximal peak force and highest EMG were used for the subsequent statistical analysis. During explosive 50% leg press, EMG signals were averaged for the whole range of motion. The best attempts during the measurements with regard to the highest average power production and highest EMG was used for the subsequent statistical analysis.

Isometric maximal voluntary trunk extensor (TrunkE) and flexor (TrunkF) force (N) was measured by using a dynamometer and an amplifier (ForAmps model-DC200G10K, Department of Biology of Physical Activity, University of Jyväskylä) with the participant in a standing position. During the extension action, the participant pushed the forceplate with the upper back and during the flexion action with the upper chest. The waist was supported by a belt and hip and knee angles were 0° and 0° (Valkeinen et al. 2008). For maximal isometric force, the participants were instructed to produce their maximal force as rapidly as possible during a time period of 2–4 s. Three to five maximal trials were recorded. The time period of rest between the maximal trials was about 1 min. A minimum of three trials was completed for each participant, and the best performance trial with regard to maximal peak force was used for the subsequent statistical analysis (Häkkinen et al. 1998).

Functional capacity tests

A 10-m walking test at maximal velocity was performed carrying a 10.2 kg bag in each hand. Walking time was recorded in seconds with photocells placed 71 cm from ground level and using a Digitest-1000 amplifier-time measurement system (10WALK) (Digi Test-1000; Digitest Ltd, Muurame, Finland). The start position was 50 cm from the photocell line and the end point was 10 m away from the first photocell line (Sipilä et al. 1996).

Balance capabilities were measured by static and dynamic tests. Static balance was measured using computerized posturography as a force platform method (Metitur Good Balance and Good Balance software 6.62; Metitur Ltd, Jyväskylä, Finland). Two standardized static standing positions with participants' eyes open (EO) and closed (EC) were utilized: (a) standard (STD) test, with the feet at a normal standing width and holding the right hand on the left wrist in front of the body; (b) the feet together (FT) test with feet together standing position and holding the right hand on the left wrist in front of the body. In both two static balance measurements, x (x)- and y (y)-directions distance (mm) and velocity momentum (mm^2 s21; Vmom) were recorded to measure the static body swaying. The measurements took 30 s in STD and FT (Fig. 1). The best of three attempts during the measurements, with regard to the least x and y directional sway, was used for subsequent statistical analysis.

Dynamic balance was measured using the same force-platform method with participants in the standard standing position. The procedure involved moving a cursor in the straightest possible line from box to box on a computer screen by shifting their weight on the force plate to record the shortest possible dynamic test distance (mm; DYN.D) (Fig. 2). The best of 3–5 attempts during the measurements with regard to the shortest distance was used for the subsequent statistical analysis. Both static and dynamic balance measurement methods have been previously shown to be reliable and valid by the normative data analysis of 7,979 subjects (Era et al. 2006).

Maximal bicycle ergometer test

The bicycle ergometer test (Ergoline ergoselect, Ergoline GmbH, Bitz, Germany) began with a 5-min warm up period at the intensity of 50 W. For the first 2-min stage of the test, the same intensity of 50 W was used and it was increased by 20 W every second minute until exhaustion. The participants were asked to maintain a pedaling rate of 60 rpm, which was monitored continuously. A 12- lead ECG was monitored (CardioSoft v.5.0, GE Medical System Corina, GE Medical INC., UK, HP computer) continuously during the test by a physician. The participants were verbally encouraged to continue cycling until volitional exhaustion. The exact time of exercise was described in minutes and seconds. Peak VO_2 ($VO_{2peak)}$ was measured breath-by-breath and averaged in 60-s intervals (Sensor Medics Vmax 229; VIASYS Healthcare Inc., Washington DC, USA). The spiroergometer was calibrated before each test and the calibration was checked after each test. Blood samples were taken from the fingertip (minilancet CCS Clean Chemical Sweden AB, Borlänge, Sweden) before the test, every second minute during the test just before changing the work load, as well as immediately, and 3 and 5 min after exhaustion for the determination of blood lactate concentrations. Blood samples were analyzed with Lactate Pro LT-1710 analyzer (Arkray Lactate pro, Arkray Factory Inc., Shiga, Japan) and the highest value after the test was used as maximal post-test lactate value (Lamax). Heart rate (HR) was measured using Polar S810i HR monitors (Polar Electro Oy, Kempele, Finland). VO_{2peak} was the highest minute average of VO_2 presented in ml kg^{-1} min^{-1} and HR_{max} was the highest HR at the end of the test (Karavirta et al. 2009).

Statistical analysis

Normal distribution and homogeneity of the parameters were checked with Shapiro-Wilk, Levene and box's tests, respectively. Statistical power between 0 and 21 weeks was also examined. Standard statistical methods were used to calculate means, standard deviation (SD) and percent changes (%). In normally distributed parameters, differences between the groups were analyzed by one-way analysis of variance (ANOVA) using the Bonferroni post-hoc test. A general linear model multivariate test (GLM) was used to calculate the difference between control period (−2 and 0 week) values and also before and after training period (0–10.5, 10.5–21, 0–21 week) values. Correlations were calculated by Pearson's product moment correlation coefficients (r).

In non-normally distributed parameters the difference between the groups were analyzed by Kruskal–Wallis test using Mann–Whitney tests. The Friedman test was used to

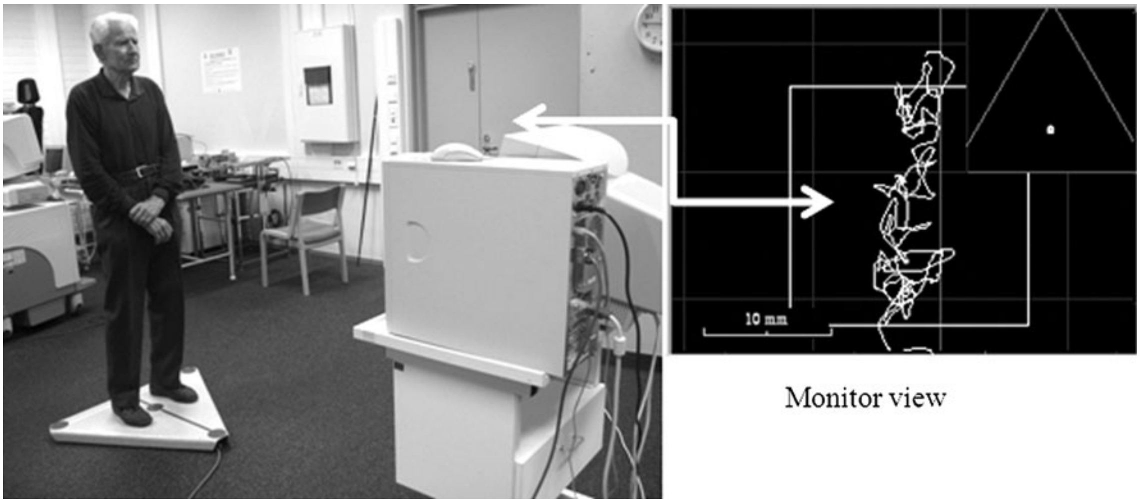

Fig. 1 The test position of subject during static balance test, an example of the recording of x and y direction body swaying, using Metitur balance measurement system

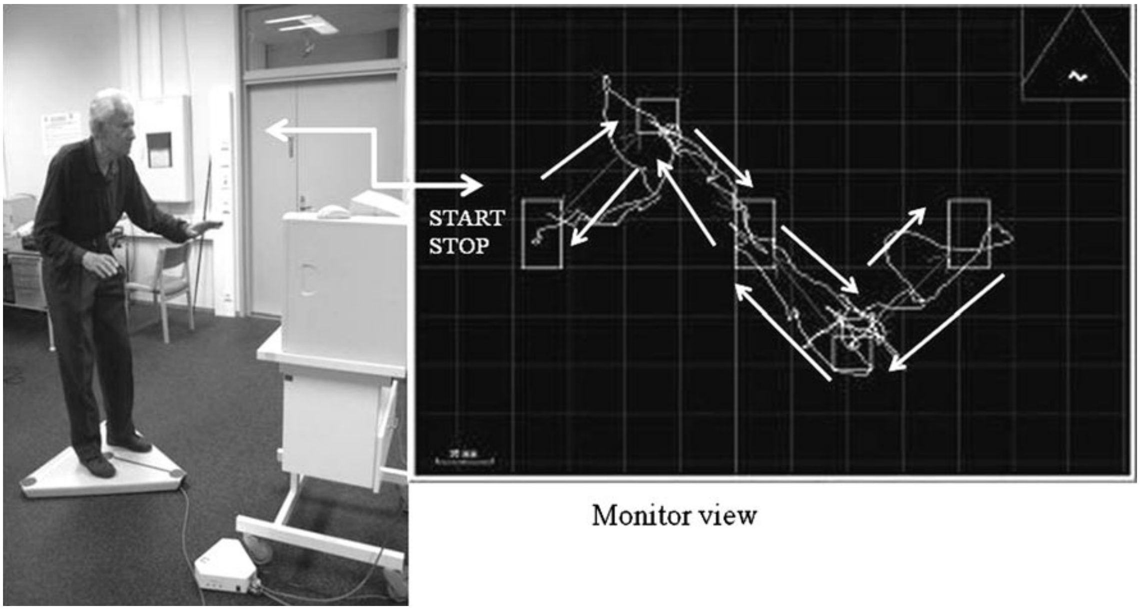

Fig. 2 The test position of subjects and course of the boxes between the start and stop points during dynamic balance using Metitur balance measurement system

calculate the difference between control period (−2 and 0 week) values and also before and after training period (0–10.5, 10.5–21, 0–21 week) values. The correlations were calculated by Spearman's rho (*r*). Statistical power between 0 and 21 weeks was calculated using Monte Carlo simulation (10,000 simulations) model. Both linear and non-linear tests statistical significances were expressed as $*p < 0.05$, $**p < 0.01$ and $***p < 0.001$.

The retrospective power analysis between 0 to 21 weeks ranged in strength variables between 0.07 and 1.00, in EMG variables between 0.00 and 1.00, in dynamic balance variables between 0.36 and 0.99, walking variables between 0.23 and 0.93 and in bicycle ergometer test variables between 0.05 and 1.00, showing adequate power to detect the differences.

Results

No significant changes were observed in any of the groups in body weight or BMI after the 21-week training period.

1RM strength

During the control period, bilateral leg press 1RM strength values increased slightly but significantly in ET ($p = 0.023$)

and C ($p = 0.046$). 1RM strength increased significantly from 0 to 10.5 weeks and 10.5 to 21 weeks of training as well as after the whole 21-week training period in all groups (Fig. 3). The changes of 5 and 8%, after 21 weeks of training in the control group and in ET were significantly (all $p < 0.001$) smaller compared to those of 21 in ST and 22% in SET.

Explosive strength

Bilateral 50% explosive leg press power did not change significantly during the control period. 50%1RMleg power increased significantly from 0 to 10.5 weeks in ST and SET, and 10.5 to 21 weeks in SET as well as after the whole 21-week training period in ST and SET (Table 2). The changes (0–21 week) in 50% 1RMleg of −1.2% in C and 2.3% in ET were significantly smaller compared to those of 10.2% in SET ($p = 0.008$; $p = 0.034$), respectively.

EMG of 1RM and explosive strength

None of the EMG variables of the 1RMleg and 50%1RMleg showed any significant changes during the control period. A significant increase in 1RM EMG of vastus lateralis between weeks 0 and 10.5 and also between weeks 0 and 21 occurred in ST (17 ± 31%, $p = 0.009$; 26 ± 40%, $p = 0.028$) and SET (21 ± 19%, $p = <0.001$; 20 ± 33%, $p = 0.002$), respectively. 1RM EMG of vastus medialis showed significant increases between weeks 0 and 10.5 and also between weeks 0 and 21 in ST (24 ± 33%, $p = 0.001$; 25 ± 34%, $p = 0.003$) and SET (15 ± 17%, $p = 0.001$; 23 ± 36%, $p = 0.002$), respectively (Table 3). The changes (0–21 week) of 1RM EMG vastus lateralis in C and ET and EMG vastus medialis in ET were significantly smaller compared to those of ST ($p = 0.033$; $p = 0.005$; $p = 0.016$) and SET ($p = 0.026$; $p = 0.004$; $p = 0.008$), respectively. The change in leg press 1RM strength in ST (10.5–21 weeks) correlated significantly but moderately with the change in 1RM EMG of vastus lateralis (10.5–21 weeks) ($r = 0.41$, $p = 0.04$). A significant increase in 50% 1RMleg EMG of vastus lateralis between weeks 0 and 10.5 and also between weeks 0 and 21 occurred in SET ($p = 0.028$; $p = 0.019$), respectively. No other significant correlations were found in any of the groups.

Isometric trunk flexion force

Isometric trunk flexion force increased significantly only in SET from 0 to 21 weeks 5.3% ($p = 0.003$). Trunk extension force increased significantly from 0 to 21 weeks in ST 13.2% ($p = <0.001$) and SET 10.8% ($p = <0.001$), while the changes of ET 4.5% and C −1.3% were minor (n.s.). The change of trunk extension force in ST was significantly larger compared to C ($p = 0.026$).

Bicycle ergometer test

In the graded bicycle ergometer test VO_{2peak} increased significantly after the 21-week training period in ET 12.5% ($p = 0.001$) and SET 9.8% ($p < 0.001$) (Fig. 4). The changes (0–21 week) of VO_{2peak} in ET ($p = 0.003$) and SET ($p = 0.010$) were significantly larger compared to C, and ST ($p = 0.001$; $p < 0.001$, respectively). Maximal blood lactate levels increased significantly after the 21-week training period in ST ($p = <0.001$) and SET ($p = 0.001$). The change (0–21 week) of MaxLa in ET

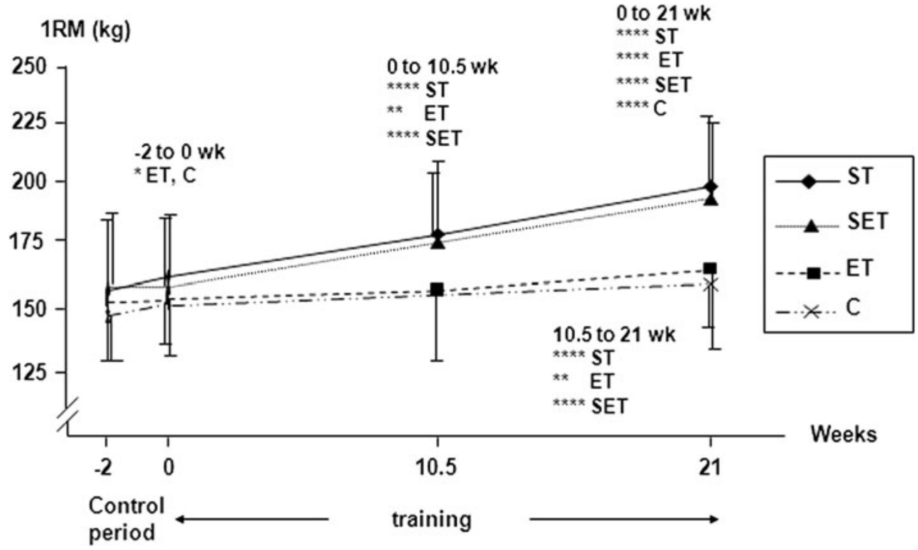

Fig. 3 Bilateral one repetition maximum (1RM) of the leg extensors during the control and training periods in the strength (ST)-, endurance (ET)- and combined (SET) training groups, and control (C) group, $*p < 0.05$; $**p < 0.01$; $***p < 0.001$

Table 2 Bilateral one repetition 50% explosive leg extension power (50% 1RMleg) during the control and training periods in the strength (ST)-, endurance (ET)- and combined (SET) training groups, and control (C) group

50% leg press average power (W)					*p* values			
Group	−2 weeks	0 week	10.5 weeks	21 weeks	−2–0 weeks	0–10.5 weeks	10.5–21 weeks	0–21 weeks
ST	799.4 ± 120.1	721.8 ± 118.2	745.1 ± 107.2	770.8 ± 117.8	0.42	0.024	0.066	0.005
ET	678.2 ± 132.1	669.6 ± 127.4	673.4 ± 125.7	683.6 ± 138.9	0.40	0.40	0.56	0.23
SET	747.6 ± 144.9	724.0 ± 152.5	762.1 ± 153.5	797.4 ± 176.5	0.69	0.002	0.010	0.000
C	637.4 ± 134.7	655.9 ± 129.6		650.2 ± 147.3	0.11			0.69

Table 3 EMG variables of the bilateral one repetition maximum (1RM) of the leg extensors during the control and training periods in the strength (ST)-, endurance (ET)- and combined (SET) training groups, and control (C) group

					p values			
Group	−2 weeks	0 week	10.5 weeks	21 weeks	−2–0 weeks	0–10.5 weeks	10.5–21 weeks	0–21 weeks
1RM leg press EMG vastus lateralis (μV)								
ST	284.9 ± 123.9	268.4 ± 120.0	308.9 ± 161.9	332.7 ± 170.9	0.82	0.009	0.072	0.028
ET	226.5 ± 87.7	241.8 ± 81.7	235.3 ± 78.6	219.9 ± 80.8	0.41	0.39	1.000	0.68
SET	260.5 ± 104.1	270.8 ± 97.4	324.6 ± 109.5	314.9 ± 114.9	0.47	0.000	0.72	0.002
C	283.5 ± 108.9	270.9 ± 102.9		268.4 ± 93.6	0.13			0.62
1RM leg press EMG rectus femoris (μV)								
ST	216.0 ± 144.0	194.6 ± 77.3	201.8 ± 88.5	204.2 ± 100.6	0.28	0.84	0.32	0.55
ET	168.6 ± 51.5	165.6 ± 60.9	160.8 ± 48.1	153.6 ± 49.6	0.68	0.53	0.84	0.32
SET	172.9 ± 63.8	178.5 ± 65.1	189.8 ± 83.3	185.1 ± 66.6	0.27	0.14	1.000	0.59
C	164.3 ± 37.9	178.4 ± 58.7		170.5 ± 51.0	0.80			0.47
1RM leg press EMG vastus medialis (μV)								
ST	236.7 ± 103.5	222.9 ± 94.1	271.5 ± 122.7	268.9 ± 113.5	0.49	0.001	0.68	0.003
ET	229.0 ± 92.2	230.1 ± 95.4	242.2 ± 91.7	212.7 ± 51.3	0.84	0.30	0.144	0.32
SET	257.6 ± 94.9	264.2 ± 102.6	305.5 ± 132.4	318.5 ± 147.1	1.000	0.001	0.11	0.002
C	259.2 ± 100.7	261.9 ± 85.6		280.4 ± 113.9	0.80			0.81

($p = 0.033$) and SET ($p = \leq 0.001$) was significantly larger compared to C, while ST ($p = 0.001$) and ET ($p = 0.022$) showed significantly smaller change than SET. No significant changes were observed in any of the groups in maximal heart rate after the 21-week training period.

Static balance

After the 21-week training period all static balance variables remained statistically unchanged.

Dynamic balance

During the control period, the total distance of the dynamic balance test changed significantly in all of the groups ($p = <0.001$ to $p = 0.025$). The total distance decreased significantly from 0 to 10.5 weeks in ST ($p = 0.023$) and 10.5 to 21 week in SET ($p = 0.011$) as well as after the whole 21-week training period in ST ($p = 0.002$) and SET

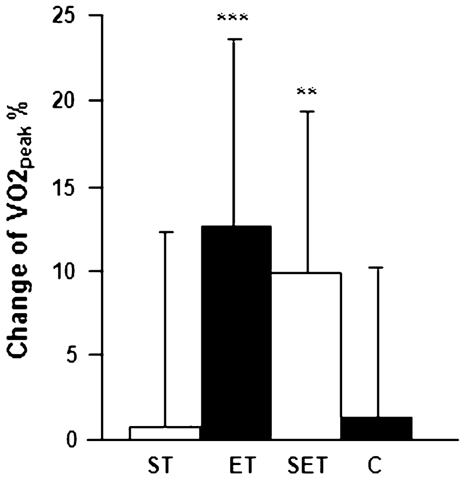

Fig. 4 A relative change of peak oxygen uptake in the bicycle ergometer test (VO_{2peak}) after the 21-week training period in the strength (ST)-, endurance (ET)- and combined (SET) training groups, and control (C) group $^{**}p < 0.01$; $^{***}p < 0.001$

Table 4 Total distance of the dynamic balance test during the control and training periods in the strength (ST)-, endurance (ET)- and combined (SET) training groups, and control (C) group

Dynamic balance (mm)					*p* values			
Group	−2 weeks	0 week	10.5 weeks	21 weeks	−2–0 weeks	0–10.5 weeks	10.5–21 weeks	0–21 weeks
ST	808.3 ± 217.6	722.5 ± 159.1	687.4 ± 128.0	639.0 ± 139.0	0.001	0.023	0.059	0.002
ET	798.1 ± 267.6	710.1 ± 204.3	699.8 ± 220.1	668.9 ± 143.4	<0.001	0.24	0.24	0.12
SET	800.3 ± 294.6	680.9 ± 135.9	670.9 ± 138.9	616.6 ± 98.8	0.003	0.72	0.011	0.028
C	896.6 ± 478.3	733.8 ± 270.3		665.1 ± 167.9	0.025			0.51

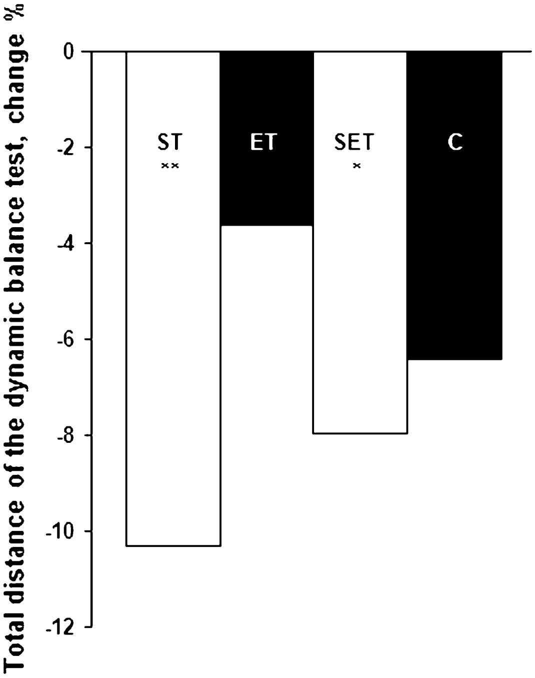

Fig. 5 Relative changes of total distance of the dynamic balance test after the 21-week training period in the strength (ST)-, endurance (ET)- and combined (SET) training groups, and control (C) group, $^*p < 0.05$ and $^{**}p < 0.01$

($p = 0.028$) (Table 4). There were no statistical differences between the groups at any measurement point. The changes after 21 weeks of training both in the control group −6.4% ($p = 0.51$) and in ET −3.6% ($p = 0.12$) were, however, smaller compared to those of −10.3% in ST ($p = 0.002$) and −8% in SET ($p = 0.028$) (Fig. 5). The total distance of the dynamic balance test correlated significantly with 1RM at 21 week in SET and ($r = -0.38$, p = 0.04) and at weeks 0, 10.5 and 21 in the total group of ST + SET (from $r = -0.29$, $p = 0.028$ to $r = -0.36$, $p = 0.006$).

The individual changes of total distance in the dynamic balance test (0–10.5 weeks) correlated significantly with changes of 50% 1RMleg (0–10.5 weeks) in ST ($r = -0.49$, $p = 0.018$). The absolute values of total distance of the dynamic balance test correlated borderline significantly with 50% 1RMleg at weeks 0 and 21 in ST ($r = -0.38$, $p = 0.077$ and $r = -0.37$, $p = 0.080$), respectively.

Ten-meter walking with the load

During the control period, 10-m walking time with a load changed significantly in ET and SET ($p = 0.006$, $p = 0.048$, respectively). Ten-meter walking time with a load decreased significantly from 0 to 10.5 weeks in all training groups ($p < 0.001$) as well as after the whole 21-week training period in ST ($p < 0.001$) and SET ($p = 0.003$) (Table 5). The change of 10-m walking time with the load at 21 week was significantly larger in ST compared to ET ($p = 0.041$) and C ($p = 0.031$). The changes of 10-m walking time with the load after 21 weeks of training were, however, smaller the in control group −1.8% ($p = 0.18$) and in ET −3.7% ($p = 0.12$) compared to those of −7.7% in ST ($p < 0.001$) and −5.3% in SET ($p = 0.003$) (Fig. 6).

Discussion

The present 21-week strength (ST) and combined strength and endurance training (SET) programs led to significant and similar increases in both maximal and explosive dynamic strength and EMG activity of the leg extensors as well as in dynamic balance and 10-m loaded walking speed. Furthermore, peak oxygen uptake of the bicycle ergometer test also increased substantially and similarly both in ET and SET, a result that is in line with previous studies conducted in older men (Wood et al. 2001; Karavirta et al. 2009; Sillanpää et al. 2009). Significant and parallel increases were observed in maximal and explosive strength characteristics in two groups that executed supervised strength training (SET and ST). Thus, the present combined strength and endurance training program (SET), did not lead to any interference effects in either strength or dynamic balance development over the 21-week training period. Therefore, the present data suggests an opportunity to achieve significant increases in strength, cardiovascular and functional capacity from a

Table 5 Ten-meter walking time with the load, carrying 10.2 kg at both hands during the control and training periods in the strength (ST)-, endurance (ET)- and combined (SET) training groups, and control (C) group

10 m walking time (s)					*p* values			
Group	−2 weeks	0 week	10.5 weeks	21 weeks	−2–0 weeks	0–10.5 weeks	10.5–21 weeks	0–21 weeks
ST	3.2 ± 0.4	3.3 ± 0.7	2.9 ± 0.3	3.0 ± 0.3	0.43	0.000	0.12	0.000
ET	3.4 ± 0.6	3.3 ± 0.5	3.1 ± 0.4	3.1 ± 0.5	0.006	0.000	0.24	0.12
SET	3.3 ± 0.5	3.1 ± 0.4	2.9 ± 0.3	3.0 ± 0.4	0.048	0.000	0.048	0.003
C	3.2 ± 0.4	3.2 ± 0.5		3.2 ± 0.4	0.25			0.18

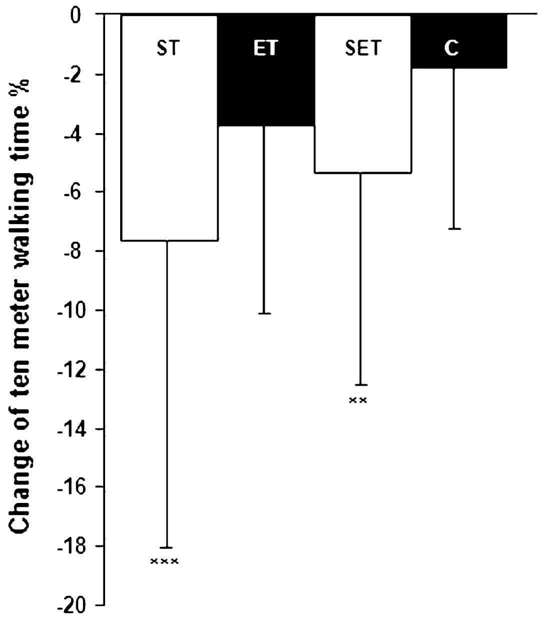

Fig. 6 Relative changes of ten meter walking time with the load after the 21-week training period in the strength (ST)-, endurance (ET)- and combined (SET) training groups, and control (C) group, $^{**}p < 0.01$ and $^{***}p < 0.001$

twice weekly training frequency (i.e. twice weekly for resistance and/or cardiovascular training, respectively) in previously untrained aging men.

EMG of vastus lateralis and medials increased significantly during the 21-week training period in the ST and SET groups. Even during the last months (10.5–21 weeks) of the present training period, the change in bilateral leg press 1RM strength correlated significantly with the change of vastus lateralis EMG in the ST group, indicating that the changes in maximal strength may have occurred mainly due to neural adaptations as reported in previous studies (Moritani and Devries 1980; Häkkinen et al. 1998, 2001). All individual muscles measured did not, however, show increases in EMG and no significant correlations with 1RM strength were observed, indicating a possible interference phenomenon in the SET group. It may be possible that the interference effect took place in the muscle fibers that are recruited during combined strength and endurance training (Hickson 1980; Kraemer et al. 1995; Bell et al. 2000). In the present study, however, the changes in maximal strength proceeded throughout the 21-week training period indicating that voluntary muscle activation can be maintained or slightly further increased during the whole training period as shown previously by Häkkinen et al. (1998). Furthermore, it may be possible that during 21 weeks of strength training muscle hypertrophy may become an important factor in contributing to the increase in maximal strength even in aging men (Fiatarone et al. 1990; Frontera et al.1988; Häkkinen et al. 1998).

None of the present groups showed any significant training-induced improvements in static balance variables during the present 21-week training period, a finding that is in line with several previous studies (Wolfson et al. 1996; Buchner et al. 1997; Bellew et al. 2003). Thus, the present results suggest that improvements in lower body or trunk strength alone do not seem to improve static standing balance. In the present study, standing static balance remained unchanged, possibly due to large individual variations and may also suggest that the present subjects were healthy and not old enough to show changes in the static balance. We did not measure all of the factors that are considered to be part of the locomotor system in the present study such as, hormonal, visual, somatosensory, vestibular and neurological factors, however, these factors are known to decline with increasing age (Whipple et al. 1993; Matheson et al. 1999; Horak 2006; Lord 2006; Jiménez-Jiménez et al. 2011). The optimal combination of exercises to improve total locomotor function as well as interactions between these multiple biological systems is still unknown. On the other hand, strength training and combined strength and endurance training are known to positively influence the postural control and balance system of older persons which should result in a better standing balance (Lord et al. 2003; Runge and Hunter 2006; Mian et al. 2007; Baker et al. 2007; Orr et al. 2008; ACSM 2009). Despite these findings, strength training intervention studies have not found significant relationships between strength training and standing static balance of healthy participants, measured by the stable force plate methods (Wolfson et al. 1996; Bellew et al. 2003; Orr et al. 2008). It is possible that static standing balance could be improved by using multimodal exercises consisting of specific balance, mobility and dynamic free weight exercises compared to these machine exercises used in the present study (Mian et al. 2007; Baker et al. 2007; Orr et al. 2008).

One of the major results of the present study and a novel finding was the improvement in the dynamic balance test in the ST and SET groups during the 21-week training period. During the control period, the total distance of the dynamic balance test changed significantly in all of the groups indicating a possible learning effect in the test before the actual 21-week training period. This learning effect, however, decreased during the training period, since the results in the control group did not change anymore during the follow-up. Therefore, our results showed an improvement in the ability of the participants to control their body's center of mass by completing the present dynamic test in a shorter distance. The present results also showed moderate correlations between dynamic balance and bilateral leg press 1RM strength of the leg extensors in the SET group at all time points. Furthermore, dynamic balance correlated modestly with the bilateral leg press 1RM strength of the leg extensors also in the ST group and the association was significant at the end of the 21-week training period. In the total group of the ST + SET participants the total distance of the dynamic balance tests correlated significantly, but moderately, with bilateral leg press 1RM strength throughout the 21-week training period. On the other hand, not only 1RM strength but also the change of explosive power correlated significantly, but modestly, with the change of total distance of the dynamic balance test in ST during the first months of the present study. Therefore, improvements in the dynamic balance may be even greater when the training program, as in the present study, includes lower extremity exercises planned not only for maximal strength development, but also for the needs of explosive strength performance.

It is suggested that aging men seem to be able to improve dynamic balance with the present type of prolonged strength training as well as combined strength and endurance training. Furthermore, the recent studies concerning strength and combined training (as well as multi modal balance and coordination training) suggest that combined training is the most beneficial training mode for the balance improvements (Mian et al. 2007; Baker et al. 2007; Orr et al. 2008). None of the variables in the stationary bicycle ergometer test, however, showed correlations with the dynamic balance capacity, a finding that is in line with the previous study by Buchner et al. (1997). Therefore, the data in the present study indicate that in aging healthy men, many factors in addition to increases in explosive and maximal strength production, such as possible changes in the neural control of balance and total locomotor systems (Horak 2006; Runge and Hunter 2006; Mian et al. 2007; Orr et al. 2008) might explain the improved dynamic balance capacity. Holviala et al. (2006) have earlier reported that strength training improves dynamic balance in aging women. Although no data with regard to falls were collected in the present study, training-induced improvements in maximal strength and dynamic balance may be beneficial even in the prevention of falls.

The present strength training and combined strength and endurance training also led to significant improvements, not only in strength characteristics and maximal oxygen uptake, but also in 10-m maximal walking speed with the load. Several studies have shown that habitual and fast walking speeds, without the load, decline during aging (Bohannon 1997) and hence has an effect on everyday functions and increased risk of falling (Rantanen 2003; Schrack et al. 2010). Nevertheless, decreased walking speed can be improved by strength training (Baker et al. 2007; Mian et al. 2007). Our results showed that whole-body strength training with a special focus on lower body exercises and combined endurance and strength training can improve the speed of ten meter walking with the load in aging men. Furthermore, this increase in 10-m walking speed with the load may indicate possible improvement in aging men's ability to perform load carrying tasks as well as everyday physical activities.

Conclusion

In conclusion, the present results showed that our aging men demonstrated training induced specific increases in strength levels of the trained muscles both in the ST and SET groups and in peak oxygen uptake both in ET and SET after the 21- week training period. Nevertheless, strength and combined training in aging men can lead not only to large increases in maximal strength of the leg extensors and of the trunk muscles, without any interference effects, but also in improvement in their walking speed with the load. Furthermore, our results showed large improvements in the dynamic balance capacity and its modest relationship with maximal and explosive dynamic strength production and of the leg extensors in the ST and SET groups.

References

American College of Sports Medicine (2000) ACSM's guidelines for exercise testing and prescription. Senior editor Franklin BA. (6th ed.). Lippincott Williams & Wilkins, Philadelphia 50

American College of Sports Medicine position stand Chodzko-Zaiko WJ, Proctor DN, Fiatarone Singh MA, Minson CT, Nigg CR, Salem GJ, Skinner JS (2009) Exercise and physical activity for older adults. Med Sci Sports Exerc 41(7):1510–1530

Aunola S, Rusko H (1984) Reproducibility of aerobic and anaerobic thresholds in 20–50 year old men. Eur J Appl Occup Physiol 53(3):260–266

Astrand I, Astrand PO, Hallback I, Kilbom A (1973) Reduction in maximal oxygen uptake with age. J Appl Physiol 35:649–654

Baker MK, Atlantis E, Fiatarone Singh MA (2007) Multi-modal exercise programs for older adults. Age and Ageing 36:375–381

Bell GJ, Syrotuik D, Martin TP, Burnham R, Quinney HA (2000) Effect of concurrent strength and endurance training on skeletal muscle properties and hormone concentrations. Eur J Appl Physiol 81:418–427

Bellew J, Yates J, Gater D (2003) The initial effects of low volume strength training on balance in untrained older men and women. J Strength Condition Res 17:121–128

Bohannon RW (1997) Comfortable and maximum walking speed of adults aged 20–79 years: reference values and determinants. Age Ageing 26:15–19

Buchner DM, Cress ME, De Lateur BJ (1997) The effect of strength and endurance training on gait, balance, fall risk, and health service use in community-living older adults. J Gerontol Med Sci 52A:M218–M224

Chtara M, Chamari K, Chaouachi M, Chaouachi A, Koubaa D, Feki Y, Millet GP, Amri M (2005) Effects of intra-session concurrent endurance and strength training sequence on aerobic performance and capacity. Br J Sports Med 39:555–560

Dudley GA, Djamilj R (1985) Incompatibility of endurance- and strength-training modes of exercise. J Appl Physiol 59:1446–1451

Era P, Sainio P, Koskinen S, Haavisto P, Vaara M, Aromaa A (2006) Postural balance in a random sample of 7, 979 subjects aged 30 years and over. Gerontology 52(4):204–213

Fiatarone MA, Marks EC, Ryan ND, Meredith CN, Lipsitz LA, Evans WJ (1990) High-intensity strength training in nonagenarians. J Am Med Assoc 263:3029–3034

Faulkner JA, Larkin LM, Claffin DR, Brooks SV (2007) Age-related changes in the structure and function of skeletal muscles. Clin Exp Pharmacol Physiol 34:1091–1096

Fleg JL, Morrell CH, Bos AG, Brant LJ, Talbot LA, Wright JG, Lakatta EG (2005) Accelerated longitudinal decline of aerobic capacity in healthy older adults. Circulation 112:674–682

Frontera WR, Meredith CN, O'Reilly KP, Knuttgen HG, Evans WJ (1988) Strength conditioning in older men: skeletal muscle hypertrophy and improved function. J Appl Physiol 64:1038–1044

Hickson R (1980) Interference of strength development by simultaneously training for strength and endurance. Eur J Appl Physiol 45:255–263

Hollenberg M, Yang J, Haight TJ, Tager IB (2006) Longitudinal changes in aerobic capacity: implications for concepts of aging. J Gerontol A Biol Med Sci 61:851–858

Holviala J, Häkkinen A, Karavirta L, Nyman K, Izquierdo M, Gorostiaga EM, Avela J, Korhonen J, Knuutila VP, Kraemer WJ, Häkkinen K (2010) Effects of combined strength and endurance training on treadmill load carrying walking performance in aging men. J Strength Condition Res 24(6):1584–1595

Holviala J, Salinen J, Kraemer WJ, Alen M, Häkkinen K (2006) Effects of strength training on muscle strength characteristics, functional capabilities, and balance in middle-aged and older women. J Strength Condition Res 20(2):336–344

Horak FB (2006) Mechanistic and physiological aspects postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls. Age Ageing 35(S2):7–11

Häkkinen K (1994) Neuromuscular adaptation during strength training, aging, detraining and immobilization: a review. Crit Rev Phys Rehabil Med 6(2):161–198

Häkkinen K, Alen M, Kraemer WJ, Gorostiaga E, Izquierdo M, Rusko H, Mikkola J, Häkkinen A, Valkeinen H, Kaarakainen T, Romu S, Erola V, Ahtiainen J, Paavolainen L (2003) Neuromuscular adaptations during concurrent strength and endurance training versus strength training. Eur J Appl Physiol 89:42–52

Häkkinen K, Kallinen M, Izquierdo M, Jokelainen K, Lassila H, Mälkiä E, Kramer WJ, Newton RU, Alen M (1998) Changes in agonist-antagonist EMG, muscle CSA, and force during strength training in middle-aged and older people. J Appl Physiol 84(4):1341–1349

Häkkinen K, Kraemer WJ, Newton RU, Alen M (2001) Changes in electromyographic activity, muscle fiber and force production characteristics during heavy resistance/power strength training in middle-aged and older men and women. Acta Physiol Scand 171(1):51–62

Ilmarinen J (1992) Job design for the aged with regard to decline in their maximal capacity: Part I–Guidelines for the practioner. Int J Ind Ergon 10:53–65

Izquierdo M, Häkkinen K, Ibañez J, Kraemer WJ, Gorostiaga EM (2005) Effects of combined resistance and cardiovascular training on strength, power, muscle cross-sectional area and endurance markes in middle-aged men. Eur J Appl Physiol 94(1–2):70–75

Jiménez-Jiménez FE, Calleja M, Alonso-Navarro H, Rubio L, Navacerreda F, Pilo-de-la-Fuente B, Plaza-Nieto JF, Arroyo-Solera M, Garcia-Ruiz PJ, Garcia-Martin E, Agundez JAG (2011) Influence of age and gender in motor performance in healthy subjects. J Neurol Sci 302:72–80

Jozsi A, Campbell W, Joseph L, Davey S, Evans W (1999) Changes in power with resistance training in older and younger men and women. J Gerontol A Biol Med Sci: Nov 54(11):M591–M596

Karavirta L, Tulppo MP, Laaksonen DE, Nyman K, Laukkanen RT, Kinnunen H, Häkkinen A, Häkkinen K (2009) Heart rate dynamics after combined endurance and strength training in older men. Med Sci Sports Exerc 41(7):1436–1443

Kasch FW, Boyer JL, Van Camp S, Nettl F, Verity LS, Wallace JP (1995) Cardiovascular changes with age and exercise: a 28-year longitudinal study. Scand J Med Sci Sports 5:147–151

Kraemer WJ, Marchitelli L, Gordon SE, Harman E, Dziados JE, Mello R, Frykman P, McCurry D, Fleck SJ (1990) Hormonal and growth factor responses to heavy resistance exercise protocols. J Appl Physiol 69(4):1442–1450

Kraemer WJ, Patton JF, Gordon SE (1995) Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. J Appl Physiol 78:976–989

Landers K, Hunter G, Wetztein C, Bamman M, Weinsteir R (2001) The interrelationship among muscle mass, strength and the ability to perform physical tasks of daily living in younger and older women. J Gerontol Ser A Biol Sci Med Sci 56A(10):B443–B448

Lord SR (2006) Visual risk factors for falls in older people. Age Ageing 35(S2):42–45

Lord SR, Menz HB, Tiedmann A (2003) A physiological profile approach to fall risk assessment and prevention. Phys Therapy 83(3):238–239

Matheson AJ, Darlington CL, Smith PF (1999) Dizziness in the elderly and age-related degeneration of the vestibular system. NZJ Psychol 28(1):10–16

Mian OS, Baltzopoulos V, Minetti AE, Narici MV (2007) The impact of physical training on locomotor function in older people. Sports Med 37(8):683–701

Moritani T, Devries HA (1980) Potential for gross muscle hypertrophy in older men. J Gerontol 35:672–682

Orr R, Raymond J, Fiatarone Singh MA (2008) Efficacy of progressive resistance training on balance performance in older adults: a systematic review of randomized controlled trials. Sports Med 38(4):317–343

Rantanen T (2003) Muscle strength, disability and mortality. Scand J Med Sci Sports 13:3–8

Runge M, Hunter G (2006) Determinants of musculoskeletal frailty and the risk of falls in old age. J Musculoskelet Neuron Interact 6(2):167–173

Ryall JG, Schertzer JD, Lynch GS (2008) Cellular and molecular mechanisms underlying age-related skeletal muscle wasting and weakness. Biogerontology 9:213–228

Seniam European Recommendations for Surface ElectroMyoGraphy (2004) Biomedical and Health Research Program. Roessingh Research and Development b.v

Schrack JA, Simonsick EM, Ferrucci L (2010) The energetic pathway to mobility loss: an emerging new framework for longitudinal studies on aging. J Am Geriatr Soc 58(Suppl 2):S329–S336

Sillanpää E, Laaksonen DE, Häkkinen A, Karavirta L, Jensen B, Kraemer WJ, Nyman K, Häkkinen K (2009) Body composition, fitness and metabolic health during strength and endurance training and their combination in middle aged and older women. Eur J Appl Physiol 106(2):285–296

Sipilä S, Multanen J, Kalinen M, Era P, Suominen H (1996) Effects of strength and endurance training on isometric muscle strength and walking speed in eldery women. Acta Physiol Scand 156(4): 457–464

Stathokostas L, Jacob-Johnson S, Petrella RJ, Paterson DH (2004) Longitudinal changes in aerobic power in older men and women. J Appl Physiol 97:781–789

Valkeinen H, Alen M, Häkkinen A, Hannonen P, Kukkonen-Harjula K, Häkkinen K (2008) Effects of concurrent strength and endurance training on physical fitness and symptoms in postmenopausal women with fibromyalgia: a randomized controlled trial. Arch Physical Med Rehabil 89(9):1660–1666

Whipple R, Wolfson L, Derby C, Singh D, Tobin J (1993) 10 altered sensory function and balance in older persons. J Gerontol48:71–76

Wolfson L, Whipple R, Derby C (1996) Balance and strength training in older adults: intervention gains and tai chi maintenance. J Am Geriatr Soc 44:498–506

Wood RH, Reyes R, Welsch MA, Favaloro-Sabatier J, Sabatier M, Lee CM, Johnson LG, Hooper PF (2001) Concurrent cardiovascular and resistance training in healthy older adults. Med Sci Sports Exerc 33(10):1751–1758