Stair-Climbing Versus Machine-Based Resistance Exercise to Improve Muscle Power Among Older Adults: A Noninferiority Trial

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Stair-climbing versus machine-based resistance exercise to improve muscle power among older adults: a non-inferiority trial

Brief running head: Stair-climbing versus machine-based resistance exercise

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ABSTRACT

Machine-based resistance training (RT) can reduce the age-related loss in muscle power (P_{max}). However, weight-bearing exercises have greater potential for implementation. This study investigated whether stair-climbing exercise (STAIR) was non-inferior to improve P_{max} compared to machine-based RT among older adults. Functional capacity tests were secondary outcomes. Older adults (30♂, 16♀; 70.9 ± 4.3 years) were randomly assigned to RT or STAIR (n=23/group). Supervised lab-based training sessions were performed 2x/week for 12 weeks. In week 1-4, exercises were performed at controlled speed (hypertrophy-oriented; 4x12-15 repetitions; 55% of one-repetition maximum (1-RM) in RT; step-up exercise with height of 30-40 cm in STAIR), in week 5-12 as fast as possible (power-oriented, 4x12 repetitions; 40% of 1-RM for RT and 4x2 flights of 6 steps for STAIR). Leg-extensor P_{max} and functional capacity were measured pre and post intervention, and P_{max} also after 4 weeks of training. Gains in P_{max} were not statistically different in RT (19.5±12.2%) and STAIR (13.7±16.5%) (d = 0.39, p_{int} = 0.086), while non-inferiority analyses were inconclusive (between-group difference in gains: 5.8% (95% CI -3.1; 14.6); non-inferiority limit 3.9%). STAIR increased more in stair ascent performance (d = 0.45-0.61, p_{int} < 0.05) than RT. STAIR and RT improved similarly on 10-m fast walk, 5-repetition sit-to-stand and countermovement jump (p_{int} > 0.05). To conclude, STAIR and RT both induced significant changes in P_{max} and functional capacity in older adults. STAIR was beneficial over RT for gains in stair-climbing performance. Future research should investigate the effects of STAIR in a home-based unsupervised setting.

Keywords: Bench stepping; Force-velocity profile; Functional capacity; Strength training; Weight-bearing exercise

INTRODUCTION

Reduced lower-limb muscle power in old age is associated with declines in functional ability (36), recurrent falls and fractures (24), increased risk for hospitalization and mortality (26) and cognitive decline (42). To prevent these negative health outcomes in older adults, gains in muscle power should be an important target in exercise strategies. As recently stated by the National Strength and Conditioning Association and by International Expert Consensus Guidelines on exercise recommendations in older adults, a properly designed resistance training program for older adults should work towards 2-3 sets of 1-2 multi-joint exercises per major muscle group at loads of 70-85% of the one-repetition maximum (1-RM), 2-3 times per week, including power exercises performed at higher concentric velocities with moderate loads (i.e., 40-60% of 1-RM) (16,20). These power-oriented resistance exercise programs can be performed safely in older adults (11,17,34) and can induce substantial gains (up to 40%) in muscle power after 12 weeks of training (38).

Although these programs can be applied in specialized exercise facilities, older adults' motivation to engage in these type of exercise programs is limited (45), stressing the need for alternative exercise strategies. Interestingly, evidence suggests that high external loads are not necessary to induce neuromuscular gains (4,8,46,48). This provides strong support for functional weight-bearing exercise intervention strategies. Stair-climbing exercise is of particular interest, as it is rated among the top five tasks as most difficult due to ageing and therefore critical in the loss of independence (49). It is a readily accessible form of exercise (29), which could ameliorate the cost-effectiveness and implementation potential of resistance exercise in older adults. Besides improvements in cardiorespiratory fitness (15,29), balance (15) and functional ability (4,15,21,23), stair-climbing and stepping-based exercises 1) can provide sufficient overload for older adults by requiring high levels of effort relative to the individual's maximum capabilities (19), 2) are highly related to leg-extensor power ($r = 0.80$, $p < 0.05$) (47), 3) induce muscular activation levels similar to high-load resistance exercise (3) and 4) result in similar or even better gains in muscle mass, strength and power compared to slow-speed resistance exercise when properly designed (4,48). Although stair-climbing or stepping-based exercises have been previously reported to improve muscle function (4,13,48), it is currently unclear whether these exercises can also induce similar gains in muscle power compared to traditional power-oriented resistance exercise in older adults. This research gap needs to be addressed, especially considering the substantial age-related decline in muscle power (i.e., -2.0 to -2.3%/year in individuals older than 60 years (2)) and its crucial role in everyday activities of older adults (36).

In any study examining effects of power-oriented resistance exercise, the velocity produced during the repetitions is an important parameter for objective monitoring of training intensity. The velocity loss that occurs within a set of repetitions, defined as the percentage drop in velocity from the fastest repetition (usually the first) to the last, is an established objective measure of level of effort (32). The higher the drop in velocity, the greater the level of effort. It is well-known that a limited drop in velocity throughout a set of repetitions (i.e., ≤ 20%) is beneficial for neuromuscular adaptations in resistance-trained young men (31). The recent work of Rodriguez-Lopez et al. (2021) on power-oriented resistance exercise in community-dwelling older adults (65+ years) confirmed that a limited drop in velocity (i.e., 5-10%) throughout a set of repetitions is effective to induce gains in muscle power and generally well-tolerated by this age group (37,38). However, it is currently not known what the optimal exercise dose in stair-climbing exercise is to induce a similar level of effort and gains in muscle power. Therefore, it is crucial that intervention studies using stair-climbing exercise in older adults monitor movement velocity. Movement velocity might also be altered by fear of falling and lack of confidence related to stair negotiation, which should be taken into account (18,44).

The current study investigated whether a 12-week weight-bearing stair-climbing exercise program (STAIR) was non-inferior for improvements in muscle power and its force-velocity (F-V) components compared to a traditional power-oriented resistance training program (RT) among community-dwelling adults aged 65-80 years. Functional capacity tests were included as secondary and exploratory outcomes. To get a better insight in the compliance and the level of effort in the exercise programs, the following outcomes were monitored throughout the program: adherence, drop-outs, fear/hesitancy to perform at maximal intent and the velocity drop during exercise. We hypothesized that STAIR would be non-inferior for improvements in muscle power and its F-V components compared to RT. This hypothesis is based on previous research, indicating the potential of stair-climbing and/or stepping-based exercises to improve muscle function in older adults (4,9,15,48).

METHODS

Experimental Approach to the Problem

This study was designed as a non-inferiority trial, comparing STAIR to RT. The intervention period was 12 weeks. The primary outcomes, i.e. muscle power and its F-V components, were obtained at baseline (pre-intervention, March-April 2022), after 4 weeks of training and within one week after the last exercise session (post-intervention, June-July 2022). The secondary outcomes, i.e. functional capacity tests, were assessed at baseline and post-intervention. Adherence and drop-outs were continuously monitored throughout the intervention, while fear/hesitancy to perform at maximal intent and the velocity drop during exercise were measured every two weeks, starting from week 6 onwards.

Subjects

Community-dwelling older adults aged 65 to 80 years were recruited through advertisements in a local newspaper. Exclusion criteria were unstable cardiovascular disease, neurological disorders, inability to understand test instructions, low level of physical function (short physical performance battery < 7), acute infections or fever, severe musculoskeletal problems, and systematic engagement of at least 1x/week in resistance exercise in the 12 months prior to participation.

Eligible subjects were randomly assigned (allocation ratio 1:1, computer-generated random schedule) to STAIR or RT in permuted blocks of two within age strata (65-72.5 years, 72.5-80 years), within sex and performance strata (baseline stair ascent power: low – high (based on reference values in our lab: low (♀ < 5.86 W/kg; ♂ < 7.55 W/kg) and high (♀ ≥ 5.86 W/kg; ♂ ≥ 7.55 W/kg)). As subjects were enrolled in the program in waves of n = 10-12 subjects per week, these strata were predetermined. Stair ascent power was chosen over leg-extensor power (=primary outcome) as stair ascent power values were immediately available after the sensor-based assessment using an automated algorithm provided by commercially available software (DynaPort MoveTest, McRoberts, The Hague, NL) (further details in methodology section for outcome functional capacity). In addition, stair ascent power is highly related to leg-extensor power (47).

An a priori sample size calculation for non-inferiority trials was performed in SampSize (app.sampsize.org.uk). As maximal leg-extensor power is our primary outcome, the inputs for the sample size calculation were based on this parameter. Based on data from N = 40 middle-aged to older adults who performed the same test protocol in our lab (33), we estimated a standard deviation of ~60W in maximal power within the study sample. The non-inferiority limit was set at 0.2 (i.e. a 20% difference between changes in both groups should be detected) as this represents a substantial improvement in leg-extensor power in mobility-limited older adults (25). Estimating a mean difference in change of 50W between intervention arms and an allocation ratio of 1, N = 19 participants should be included in each of the intervention groups ($\alpha = 0.05$, power = 0.80). Accounting for a potential drop-out of 15%, N = 23 participants per group were recruited (Figure 1). Subjects' characteristics are described in Table 1. There were no statistically significant between-group differences at baseline.

The study was conducted at XXX, approved by the Ethical Committee XXX (XXX) in accordance with the most recent version of the Declaration of Helsinki and registered as clinical trial on clinicaltrials.gov (XXX). All subjects were informed of the risks and benefits of the study prior to signing an institutionally approved informed consent document to participate in the study.

insert Figure 1 and Table 1

Procedures

Intervention. For both STAIR and RT, the training sessions were performed twice a week (Tuesdays and Thursdays) over a period of 12 weeks (24 sessions in total). All sessions were performed in a lab-based gym setting and supervised by a qualified master in movement and sport sciences with more than 10 years of experience as fitness coach. A standard 10-minute warm-up was performed on a cycle ergometer (Technogym, Bike Excite) at self-selected resistance and 70-80 revolutions per minute. The program included both lower and upper body exercises. Lower-body exercises differed between both groups (see RT program and STAIR protocol), but the same upper-body resistance exercises were used to provide a full-body exercise program for the participants, i.e., chest press and low row (Life Fitness, Optima Series). For these upper-body exercises, training volume was set at 2 x 12-15 repetitions until volitional fatigue (i.e., close to failure), with 1-min interset rest. Training load was increased when participants were able to perform repetitions beyond the pre-set range.

Lower-body exercises in RT protocol. A pneumatic horizontal leg press device (Leg Press CC, HUR, Kokkola, Finland) was used to perform multi-joint leg extensions. Exercises were performed unilaterally to match the movement of a step-up and stair-climbing exercise (see STAIR protocol). From week 1 to 4, participants performed 4 x 12-15 repetitions until volitional fatigue (2 sets per leg, legs were alternated between sets) with 45s interset rest at controlled velocity (2s concentric, 2s eccentric). Load was initially set at 55% of the one-repetition maximum (1-RM) and gradually increased when participants were able to perform repetitions beyond the pre-set range. From week 5 to 8, participants performed 4 x 12 repetitions at 40% of 1-RM with 45s interset rest, with the concentric phase as fast as possible (i.e., including a flight phase) and a controlled velocity during the eccentric phase (2s). An additional warm-up set was provided per leg (2 x 12 repetitions at 50% 1-RM). At week 9, the load was increased by 10%, while all other training variables remained the same for the last 4-week period (Table 2). In the first training session of weeks 6, 8, 10, and 12, mean concentric velocity was measured for repetition 1 and 12 in each set (see leg-extensor F-V methodology below) to have an indication on the velocity loss throughout the sets.

Lower-body exercises in STAIR protocol. As it is not possible to exactly match training dose between RT and STAIR (e.g., because of differences in joint angles, range of motion and loads), we matched the protocols on type of exercise (i.e., unilateral leg-extension movements), number of repetitions performed per leg, intended velocity and interset rest periods. A step-up box (30 or 40 cm) and two flights of 6 stairs were used as training equipment for the same muscle groups as RT. From week 1 to 4, participants performed 4 x 12-15 repetitions of a forward step-up exercise on a box (2 sets per leg, legs were alternated between sets) with 45s interset rest at controlled velocity (2s concentric, 2s eccentric). Starting height of the box was 30 or 40 cm and load equaled body mass. Progression was built in by increasing step height (to maximum 40cm) and/or by adding a weight vest (10% of body mass). From week 5 to 8, the forward step-up was used as a warm-up exercise (2 x 12 repetitions with body mass). After this warm-up exercise, participants were asked to climb two flights of 6 stairs as fast as possible (with a 180° turn between the two flights), without using the handrail or skipping a step. This exercise was performed 4 times, with 45s interset rest (which included stair descent at slow pace). At week 9, load was increased by adding a weight vest (10% of body mass), while all other training variables remained the same for the last 4-week period (Table 2). In the first training session of weeks 6, 8, 10, and 12, mean vertical velocity of every single step during stair ascent was measured with a body-fixed sensor (see stair ascent methodology below) to have an indication on the velocity loss throughout the sets.

insert Table 2

Sample characteristics. Level of education and presence of chronic conditions were collected at baseline by means of a questionnaire. Body height and mass were determined using a stadiometer and a digital scale (Seca, GmbH & Co. KG, Germany), respectively. All participants wore minimal clothing and were barefoot. Body mass index (BMI) was calculated as body mass (kg) divided by squared body height (m).

Compliance to the exercise program and level of effort. During the intervention, drop-outs were documented, exercise session adherence was calculated as the number of training sessions performed relative to the preprogrammed number of sessions (i.e., 24), velocity loss and fear/hesitancy to perform at maximal intent were monitored every 2 weeks (week 6, 8, 10 and 12). More specifically, immediately after the first training session of week 6, 8, 10 and 12 in both RT and STAIR, the following questions were answered by the participants on an 11-point Likert scale, ranging from 0 = 'not at all …' to 10 = 'very …': (1) How much fear did you experience to perform at maximal velocity? (2) How hesitant were you to perform at maximal velocity? Measurements of velocity during exercise were performed using the methodology of the leg-extensor F-V profile (in RT) and the stair-ascent test (in STAIR) (see below for details). In RT, the loss in velocity throughout a set was calculated as the percent change in mean velocity from the first to the last repetition. It is challenging to measure velocity loss during a stair-climbing event. We used the mean vertical velocity during every single rise phase of a step measured with a body-fixed sensor (see below for details), but we cannot compare the first and last step of a stair. During a 6-step stair event, the highest mean velocity or power is typically reached at steps 2 to 4, while subjects tend to slow down in steps 5 and 6 (see results section). This slowing down is not related to fatigue, but to a braking phase near the end of the stair (as we do not see this decline in a 12-step stair test) (28). Therefore, the current study compared the mean vertical velocity of the second flight of 6 steps to the mean vertical velocity of the first flight of 6 steps as a measure of effort.

Leg-extensor F-V profile. After a familiarization session to get acquainted with the equipment and test protocol, F-V profiling was carried out unilaterally (dominant leg) on the same pneumatic leg press device (Leg Press CC, HUR, Kokkola, Finland) as the training sessions in RT. Seat inclination was 130° and the inclination of the apparatus was 5° to horizontal. Instantaneous force was measured at the foot plate by four built-in load cells and displacement of the seat by a built-in potentiometer. Detailed procedures of the test protocol can be found elsewhere (33). A standardized warm-up was performed, i.e., a 10-min warm-up on a cycle ergometer at self-selected load and three sets of practice trials with 1-min interset rest. The test protocol consisted of a maximal isometric test (knee joint angle = 85°, hip angle = 55°; 3 attempts of 3s) and explosive concentric leg extensions at gradually increasing loads (5%, 15%, 30%, 45%, 60% of the maximal isometric force, 2 (for 45% and 60%) to 3 (5%, 15% and 30%) attempts per load, and additional single repetitions until the 1-RM was reached). Standardized rest periods were provided (1). This full protocol was used at baseline and post intervention, but shortened for a less time consuming alternative at the intermediate test moment at the end of week 4. In the shorter version, no isometric test was performed and the same loads as during the baseline assessment were used. The test ended after the 60% load, without performing single repetitions to reach 1-RM. To calculate training load for week 5 in RT, 1-RM was estimated based on the F-V profile for participants in RT. Analyses of the baseline data comparing the F-V profile with all data points to the F-

V profile with only the 5 first data points showed excellent agreement on all variables extracted from the profile (see below for variables; ICC = 0.90 – 0.99; CV% = 1.2 – 2.5). This indicates an excellent level of agreement between both methodologies. Also, 1-RM estimated from the F-V profile (5 data points) was highly accurate (ICC = 0.91; CV% = 6.3).

All data (time and position) were relayed to a pc via an AD converter, recorded using LabVIEW (version 2016) and processed offline using Matlab (version R2023a). Data were sampled at 1000Hz and filtered by a fourth-order low-pass Butterworth filter with a 70 Hz cut-off frequency. Mean velocity of all concentric trials was calculated as the displacement of the seat over time (from the start of the movement until full extension (knee angle 180°)), the potential flight phase during light loads was discarded. The best trial per load (i.e., highest mean velocity value) was selected. From this trial, the mean velocity and corresponding force were used to estimate the individual F-V relationship through a linear equation (1,33):

$$F = F0 - aV$$

where a is the slope and F_0 the F-intercept observed under zero V. To note, total system load was calculated (i.e., external load + body mass + weight of seat corrected for inclination) as proxy to force. Data points that deviated from the expected linear regression with more than 0.03 m s^{-1} were excluded (1). On average, 4.6 ± 1.3 data points were used to estimate the F-V relationship. Individual R^2 values of the linear regression were all higher than 0.97, indicating an excellent fit of the linear regression line on the data points. For an overview and reliability values of the F-V procedure, see Alcazar et al. (1).

From the individual F-V regression lines, the following variables were extracted: force at zero velocity (F_0, theoretical maximal isometric force, N), velocity at zero load (V_0, maximal velocity, m s^{-1}) and the slope divided by F_0 (S_{FV}/F_0, decline in force as a function of velocity). Maximal muscle power (P_{max}, W) was calculated using the following equation:

$$Pmax = F0 * V0/4$$

(F_0 x V_0)/4. 1-RM was defined as the highest load (total system load, N) that an individual was able to push throughout the full range of motion. Reliability data for these parameters in our lab were good to excellent, with ICC ranging from 0.82 to 0.93 and CV% from 4.4 to 7.5.

Functional capacity. A test battery was used, consisting of 10-m fast walk, countermovement jump (CMJ), 5-repetition sit-to-stand (5xSTS) test and a 3-step and 6-step stair ascent (SA) test. For the 10-m fast walk, participants were instructed to walk as fast as possible, and time (s) was registered through timing gates (Racetime2 Light Radio, Microgate, IT) (ICC = 0.75, CV% = 5.88). A maximal CMJ was performed on a contact mat with the hands on the hips and jump height was calculated based on previous procedures (ICC = 0.94, CV% = 5.17) (22). During the 5xSTS and SA test, linear and angular acceleration data were collected using a body-fixed sensor positioned at the lower back (DynaPort MoveTest, McRoberts, The Hague, NL), including tri-axial accelerometers and gyroscopes. Sampling rate was 100Hz and data were analyzed using commercially available software (DynaPort MoveTest, McRoberts, The Hague, NL). Quality control of the automated software algorithms was performed by checking the visualization of the vertical position (for SA) and trunk angle (for 5xSTS) over time in the report provided by the software. When the software generated incorrect markings of SA steps or STS repetitions, the test was repeated. A detailed overview of the procedure can be found in our previous work (47). Briefly, participants were asked to perform five sit-to-stand cycles as fast as possible with the arms crossed over the chest (back touching the chair in every repetition). Total STS duration (s) (from start until fifth standing position) and mean power during the sit-to-stand transition phase were calculated from the sensor data (ICC = 0.74-0.93; CV% = 5.9-7.2). In the SA test, participants ascended a flight 6 stairs as fast as possible without using the handrail. Total SA duration (s), mean velocity and mean power (W) during the rise phase (defined as vertical velocity > 0.1 m/s) of each step were calculated. SA power was then averaged for the 6 steps. Reliability values for the 6-step staircase are reported elsewhere, with ICC ranging from 0.90 to 0.94 and CV% from 5.4 to 9.0 (28).

Two (5xSTS) or three (all other tests) trials were performed and the best trial (based on duration parameter or jump height) was used in the analyses.

Statistical analyses

Data were presented as mean ± standard deviation (SD) unless otherwise stated. Baseline differences between groups were tested with independent samples T-tests or Mann-Whitney U tests (non-normal distribution) for continuous variables and with Chi-square tests for categorical variables. The mean change in velocity throughout a set of repetitions in RT and STAIR is visualized in a line graph. To note, the DynaPort MoveTest software was not designed to analyze multiple flights of stairs. Therefore, we carefully checked each trial captured during the exercise sessions on incorrect markings of steps by the software. This check was based on the visualization of the vertical position in the automated report provided by the software. Two flights of six steps should clearly indicate: six steps, a longer phase of no change in vertical position, followed by another six steps. When the trial deviated from this format, it was removed from the analyses. In total, 230 valid trials were analyzed.

As this study was considered a non-inferiority trial, the primary analysis was the comparison of the percent changes (post – baseline) of the F-V variables between RT and STAIR. An independent samples T-test on the percent changes was used to define the mean difference (including 95% confidence intervals (CI)) between RT and STAIR (i.e., RT – STAIR). If the non-inferiority limit, defined as 0.2 x mean % change in RT, was greater than the upper limit of the CI of the mean difference, STAIR was considered as non-inferior to RT.

In addition, traditional superiority analyses were performed. More specifically, the effects of the intervention on all outcomes were tested by linear mixed-effects models with a random factor (participant ID) and three terms: intervention group (RT [code = 1] vs STAIR [code = 2]), time (baseline and post-intervention) and time-by-group interaction. To note, for the variables derived from the F-V profile, three time points were introduced in the analyses (baseline, after 4 weeks of training, and post-intervention). Beta coefficients (including 95% confidence intervals (CI)) of linear mixed-effects models and Cohen's d effect sizes for between-group differences in absolute changes from baseline to post-intervention were reported for all variables with a p-value lower than 0.1 for the time-by-group interaction effect. Thresholds 0.20, 0.50 and 0.80 were used to interpret small, medium and large effect sizes (12). Post-hoc analyses using paired-samples T-tests were conducted for within-group changes when the time-by-group interaction effect was significant.

To test the assumptions for multilevel regression models, we checked whether the models' residuals were normally distributed, both by visual inspection of the Q-Q plots and histogram as well as by Shapiro-Wilk tests. If the residuals were non-normally distributed, a log or square-root transformation was performed, depending on which transformation yielded normally distributed residuals. The following parameters were not normally distributed and transformed: P_{max} (log transformed), F_0 (log transformed). Non-normality remained after transformation of one variable: 6-step stair ascent duration. For this variable, non-parametric tests were used. Overall time effect from baseline to post was analyzed with Wilcoxon Singed Rank tests. Percent change from baseline to post was compared between groups with Mann-Whitney U tests.

All statistical tests were conducted in R (version 4.2.1). The multilevel models were fit using the lmer-function of the lme4 package. Level of significance was set at $p < 0.05$.

RESULTS

There were no statistically significant between-group differences for any of the outcome variables at baseline.

Compliance to the Exercise Program and Level of Effort

Two male participants in RT dropped out, one in week 6 and one in week 11. Reasons for drop-out were familial circumstances and a bike accident (see Figure 1). Overall adherence to the program, excluding these two drop-outs, was high: 94.8 ± 6.3% in RT and 91.8 ± 4.8% in STAIR. All participants were high adherers (adherence ≥ 80%).

On average, the change in velocity from the first to the last repetition was -6.9 ± 11.2 % during exercise in RT. In STAIR, an increase in velocity of 17.1 ± 15.0 % was found when comparing the second flight of steps to the first flight (Figure 2, black line). Additional detailed analyses were performed to address changes in velocity over time (from week 6 to week 12) and between sets, but these analyses go beyond the research questions of this study and were therefore added as a supplementary information (supplementary Table 1).

Four subjects in STAIR and two in RT indicated that fear impeded them from performing maximally (defined as grading of 6 or more on Likert scale) in week 6 and two subjects in STAIR maintained this hesitancy throughout the training period.

insert Figure 2

Leg-extensor Power and its F-V Profile

All F-V variables showed a significant improvement over time ($p < 0.05$). For S_{FV}/F_0, the significant time effect indicates a less steep slope at post-intervention compared to baseline ($p < 0.001$), reflecting a greater change in V_0 compared to F_0. No significant between-group differences were found for post-intervention gains in P_{max} (19.5 ± 12.2% in RT versus 13.7 ± 16.5% in STAIR, $d = 0.39$, $p = 0.086$), nor in any of the F-V variables (all $p > 0.05$) (Figure 3). Non-inferiority tests were inconclusive for all F-V variables, as evidenced by the 95% CI of the mean differences between RT and STAIR overlapping the non-inferiority limit (Figure 4).

insert Figure 3 and Figure 4

Functional Capacity

All functional capacity tests showed a significant improvement over time ($p < 0.05$). As demonstrated by a significant time-by-group interaction effect, STAIR improved significantly more than RT on 6-step stair ascent power (+13.3 ± 13.5% in STAIR versus +4.9 ± 13.9% in RT; β = 0.08 [95% CI 0.01 – 0.15], *d* = 0.61, p = 0.035) and on 6-step stair ascent duration (-13.1 ± 9.6% in STAIR versus -5.7 ± 7.8% in RT; *d* = 0.45, p = 0.007). No time-by-group interaction effect was found for 5xSTS power (+8.5 ± 14.2% in STAIR versus +1.6 ± 9.4% in RT; β = 18.58 [95% CI -2.65 – 39.92], *d* = 0.67, p = 0.087), 5xSTS duration (p = 0.197), 10-m fast walk (p = 0.263) and CMJ jump height (p = 0.686) (Table 3).

insert Table 3

DISCUSSION

The current study investigated whether a weight-bearing stair-climbing exercise program was non-inferior for improvements in muscle power compared to a machine-based power-oriented resistance training program among community-dwelling older adults. Functional capacity was included as secondary outcome. The results showed that 1) both groups induced significant changes in leg-extensor power and its F-V components, although non-inferiority analyses remained inconclusive, and 2) STAIR was superior to RT for improvements in stair-climbing performance.

In line with previous research (11,14,35,38,40), machine-based power-oriented resistance training at moderate load induced marked gains in leg-extensor power in this study (+19.5 ± 12.2%). Adaptations were greater in the high- compared to the low-velocity region of the F-V spectrum, which was evidenced by a change in the slope (i.e., less steep at post-intervention compared to baseline). This result confirms previous work by Rodriguez-Lopez et al. (38), who reported that power training at 40% of 1-RM resulted in an improved capacity to produce force at high velocities. A novelty of the current study is that we additionally investigated the effects of a functional stair-climbing exercise program and compared those to traditional power-oriented resistance training. Although the current study confirmed that STAIR can induce significant changes in leg-extensor power and that RT is not statistically superior to STAIR, non-inferiority analyses remained inconclusive. Important to note is the challenge to identify a clinically relevant difference. As a 20% gain in leg-extensor power was previously defined as a substantial change in mobility-limited older adults (25), we decided to use this threshold. However, future research should investigate the clinical relevance of this threshold in well-functioning older adults.

According to the principle of training specificity, the more the test condition resembles the training exercise, the better the results will be (10). The movement pattern was identical during the F-V assessment and the training exercise in RT, which could have led to greater improvements on P_{max}, although no statistical differences were found in post-intervention gains between RT and STAIR. Interestingly, the F-V assessment after 4 weeks allowed us to investigate the time course of the changes. In the initial 4-week training phase, gains in leg-extensor power were similar between RT (10.0 ± 11.2%) and STAIR (9.6 ± 11.3%). As reported previously, exercise program design might play a minor role in the immediate adaptations from an unfamiliar exercise stimulus (43). Gains in V_0 seemed to stagnate from week 5 to week 12 in STAIR, leading to (non-significantly) lower improvements in P_{max}. Whether these results can be explained by a lack of training specificity in movement velocity and pattern, by an insufficient training stimulus or by a hesitancy of the participants to perform at maximal velocity (as stair-climbing velocity increased throughout sets) remains to be investigated.

It should be noted that it was not possible to exactly match training intensity (i.e., load, intent and effort) between STAIR and RT, which may have influenced the results. The number of repetitions and inter-set rest periods were matched, an identical progression was used throughout the training weeks, and participants were asked to perform at maximal intended velocity (from week 5 onwards). Effort was objectively measured throughout the training sets. In RT, the velocity loss within a set was on average -6.9%, which has previously been identified as beneficial for neuromuscular adaptations (31). In addition, it is well tolerated by older adults, as it results in limited metabolic stress and muscle damage (37). In STAIR, no signs of fatigue were found, with an average increase in velocity instead of a drop in velocity throughout the flights of stairs. To note, a large interindividual variability was found for these changes in velocity throughout the sets (both in RT and STAIR), as demonstrated by large SD's. This is in line with previous research demonstrating that the number of repetitions that can be completed against a given % 1-RM is highly variable (39), which results in different levels of effort between individuals when performing a fixed predetermined training volume. Despite the large interindividual variability in level of effort, a velocity loss was noticed in 77% of the sets in RT versus in only 13% in STAIR. This indicates that overall effort was probably higher in RT compared to STAIR. . The increase in velocity towards the second flight of the stair might be related to the individual's anticipation on the turn between both flights, causing an unintentional slowing in the first flight. Figure 2 supports this claim, as subjects seem to perform worse in the first flight compared to the reference test of 6 steps. Performance in the second flight of 6 steps is very similar to the reference test, although more vertical velocity is generated in the first two steps of the second flight. This might be explained by a difference in starting point, i.e. a dynamic start instead of from standing still (more difficult to generate power). Previous research in 116 community-dwelling older adults aged 65+ years did demonstrate a fatigue-related drop of -8.7% in power production during 12-step stair ascent performed at maximal velocity, so the results in the current study might have been different if a flight of 12 steps was used instead of two flights of 6 steps (28). As mentioned in the introduction section, fear of falling and confidence related to stair negotiation might also alter movement velocity during stair ascent (18,44). In the current study, subjects appeared to build confidence throughout the different sets, demonstrated by increased movement velocity. Given that only a very limited number of subjects indicated that they were hesitant to perform at maximal velocity, a lack of maximal intent is probably not the main reason for differences between RT and STAIR. Future research should investigate whether training adaptations can be optimized in stair-climbing exercise by increasing training dose. Potential strategies could be the use of higher loads through weighted vests (9,27), increasing the training volume, using longer flights of stairs or increasing the step height by skipping a step (15).

An important consideration in exercise interventions for older adults, is whether neuromuscular adaptations also result in improved functional capacity. In line with task-specificity of adaptations, a recent paper of Pagan et al. demonstrated that a functional exercise program, including exercises that mimic activities of daily living in older adults, outperformed traditional resistance training for gains in functional capacity (30). In addition, previous studies in older adults reported greater improvements in sit-to-stand performance, countermovement jump and/or stair-climbing performance after plyometric exercise programs with step-up jump exercises in comparison to traditional resistance training (13,48). In the current study, STAIR was superior over RT to improve stair-climbing performance, which can be attributed to specificity of training. It is less clear whether the findings can also be translated to improved functioning in other daily life activities. However, both power-oriented resistance training and weight-bearing stair-climbing exercise can induce a positive effect on functional capacity tests that require lower-limb power production at moderate to high velocities, including fast walking, jumping, chair rising and stair climbing (4,7,9,13,27,48).

The following limitations of the current study should be acknowledged. Firstly, no major claims on non-inferiority of STAIR versus RT could be made given the limited sample size. Secondly, only community-dwelling physically well-functioning older adults were included, of which the majority was also cognitively well-functioning and highly educated. Results cannot be generalized to the overall older population. Thirdly, the training period was limited to 12 weeks. As exercise specificity is more crucial in later phases of the training process, potential differential adaptations of STAIR and RT need to be investigated in longer-term interventions. A strength of this study is the use of a pneumatic leg press device, specifically designed to perform high-velocity training safely. Previous research in community-dwelling older adults (≥ 60 years) demonstrated similar gains in muscle power and physical function using either pneumatic or plate-loaded machines (6), indicating that our results would probably have been similar with the use of plate-loaded instead of pneumatic machines. The question arises whether free-weight RT would have resulted in greater functional improvements (e.g. on stair-climbing and sit-to-stand performance) compared to our machine-based RT, as free-weight RT is believed to mimic more everyday activities. Previous research findings in older adults did not indicate superiority of free-weight RT over machine-based RT for increasing overall muscle strength (41). Moreover, the superiority of free-weight RT over machine-based RT for improvements in everyday function of older adults remains an assumption and needs to be investigated in future research. An important consideration to bear in mind is that free-weight RT demands increased safety precautions (41), particularly when performing exercises at high concentric velocities, which justifies the use of machine-based RT in novice older adults.

To conclude, both stair-climbing exercise as well as machine-based power-oriented resistance training can induce statistically significant changes in leg-extensor power and functional capacity among community-dwelling older adults. No claims can be made regarding non-inferiority of stair climbing compared to machine-based resistance training.

PRACTICAL APPLICATIONS

Twelve weeks of either stair-climbing exercise or machine-based power-oriented resistance training can induce marked gains in leg-extensor power in previously untrained community-dwelling older adults. More favorable gains in task-specific functional tests were found for stair-climbing exercise. These greater functional gains in combination with a greater potential for large-scale implementation might make the intervention more effective in real-life settings. Currently, international consensus guidelines for exercise in older adults recommend a multi-modal exercise prescription for optimal ageing, including aerobic, resistance and balance training. However, to achieve optimal levels of adherence, experts suggest to start with a single exercise modality to allow the older adult to gradually adapt to the new exercise routine (5,20). In this regard, stair-climbing or stepping-based exercises might constitute a promising, time efficient and easily accessible exercise modality, targeting improvements in cardiorespiratory function, muscle function and balance (4,9,15). We should however bear in mind that future research is necessary to investigate 1) the optimal exercise dose and progression of stair-climbing and stepping-based exercise over a longer-term intervention and 2) the effects of such exercise programs when implemented in a home-based setting with limited expert oversight.

ACKNOWLEDGEMENTS

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DECLARATION OF COMPETING INTEREST

None declared.

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FIGURE LEGENDS

Figure 1. Flow chart of the study.

Figure 2. Plots of the mean velocity produced during the leg press exercise for repetition 1 and 12 within a set (right leg) and during the stair-climbing exercise for each step. For the stair-climbing exercise, both the training exercise with two flights of six steps (black line) with a 180° turn in the middle (between step 6 and 7, no vertical velocity so not presented here) and the reference test with one flight of six steps (blue dotted line) is presented. To note: the same blue dotted line was repeated for steps 7 to 12 to be able to compare both the first as well as the second flight of six steps with the reference test of six steps. The mean percent change in velocity from repetition 1 to 12 (RT = resistance training group) and from flight 1 to 2 (STAIR = stair-climbing exercise group) is noted in red. Error bars represent 95% confidence intervals.

Figure 3. Plots above represent estimated means and SE at baseline, week 4 and post-intervention for P_{max}, F_0 and V_0 in the resistance training (RT – black) and stair-climbing exercise (STAIR - blue) group. P-values of time x group interaction effects using Linear Mixed-Effects Models are added. P_{max} and F_0 were log transformed for the analyses because of non-normality, but non-transformed data means were reported for easier interpretation. Plots below represent individual changes in P_{max}, F_0 and V_0 in both exercise groups.

Figure 4. Forest plot of mean difference in percent changes (RT – STAIR) and 95% confidence intervals for maximal power (P_{max}), theoretical maximal isometric force (F_0) and maximal velocity (V_0). The red vertical line represents the non-inferiority limit, defined as 0.2 x mean % difference in RT.

Figure 1

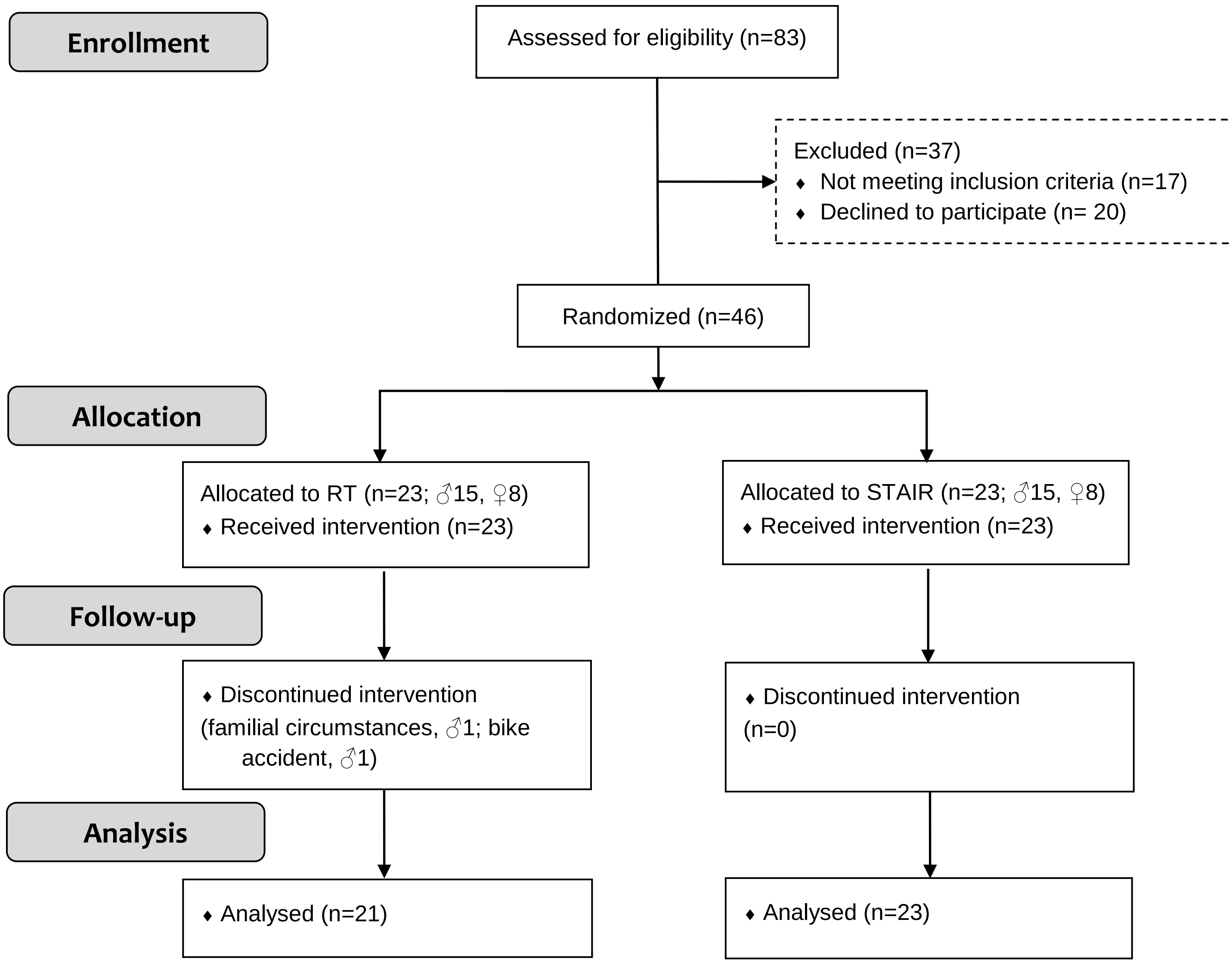

Enrollment
Assessed for eligibility (n=83)
Excluded (n=37)
♦ Not meeting inclusion criteria (n=17)
♦ Declined to participate (n= 20)
Randomized (n=46)
Allocation
Allocated to RT (n=23; ♂15, ♀8)
♦ Received intervention (n=23)
Allocated to STAIR (n=23; ♂15, ♀8)
♦ Received intervention (n=23)
Follow-up
♦ Discontinued intervention (familial circumstances, ♂1; bike accident, ♂1)
♦ Discontinued intervention (n=0)
Analysis
♦ Analysed (n=21)
♦ Analysed (n=23)

Figure 2

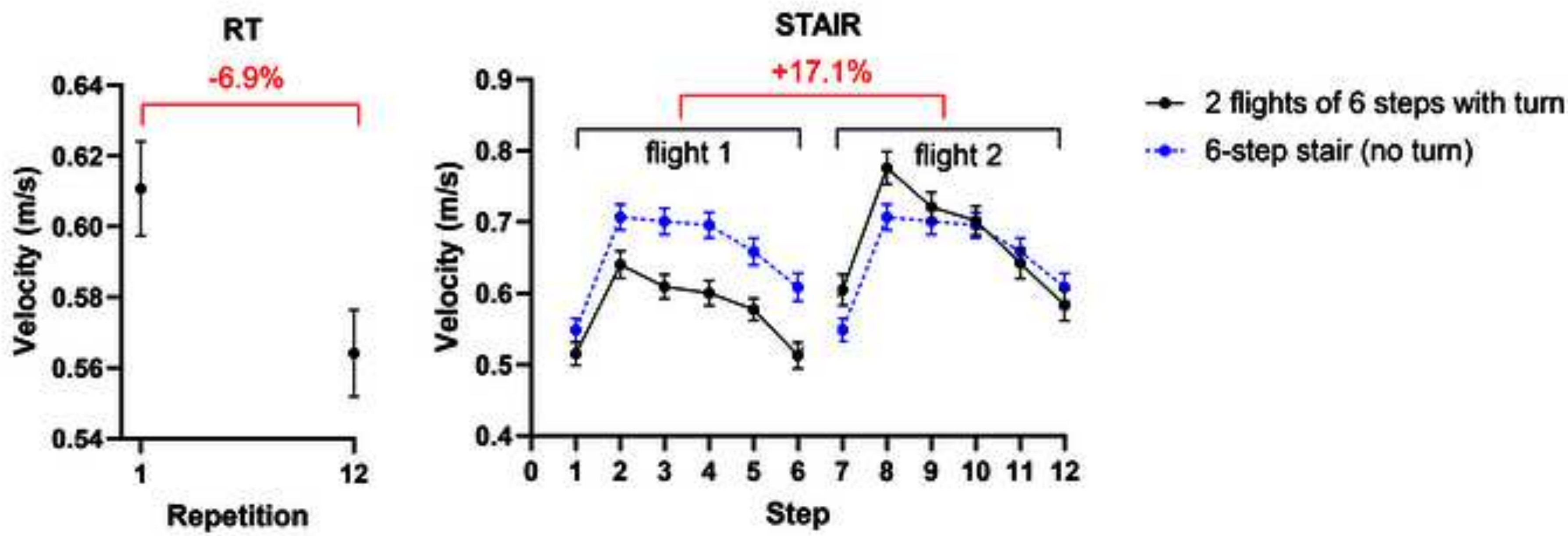
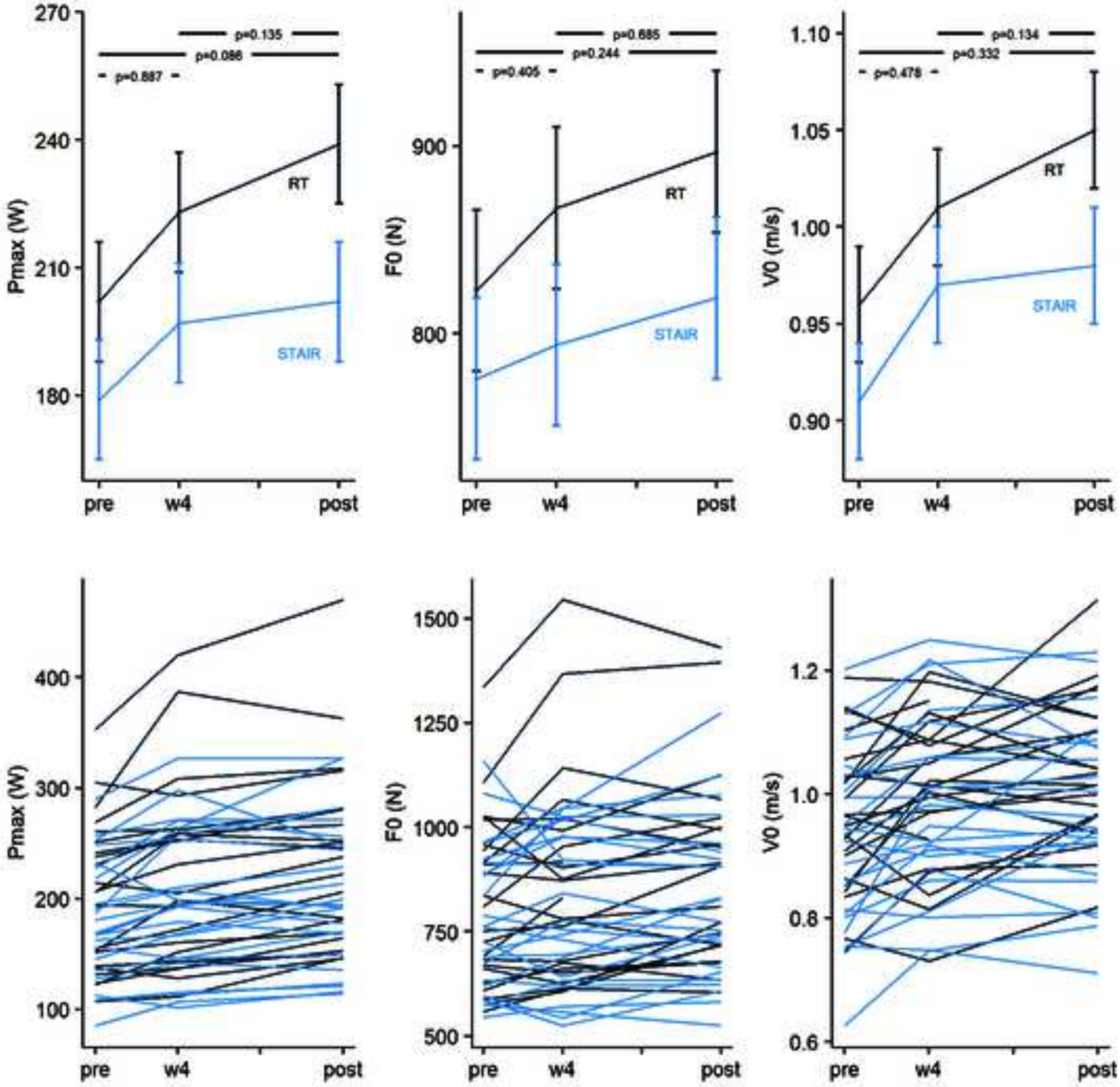

RT
-6.9%
0.64
0.62
0.60
0.58
0.56
0.54
Velocity (m/s)
1
12
Repetition
STAIR
+17.1%
0.9
0.8
0.7
0.6
0.5
0.4
Velocity (m/s)
flight 1
flight 2
0 1 2 3 4 5 6 7 8 9 10 11 12
Step
2 flights of 6 steps with turn
6-step stair (no turn)

Figure 3



p=0.135
p=0.086
p=0.887
RT
STAIR
Pmax (W)
270
240
210
180
pre
w4
post
p=0.685
p=0.244
p=0.405
F0 (N)
900
800
p=0.134
p=0.332
p=0.478
V0 (m/s)
1.10
1.05
1.00
0.95
0.90
400
300
200
100
1500
1250
1000
750
500
1.2
1.0
0.8
0.6

Figure 4

Click here to access/download;Figure;Figure 4.tif

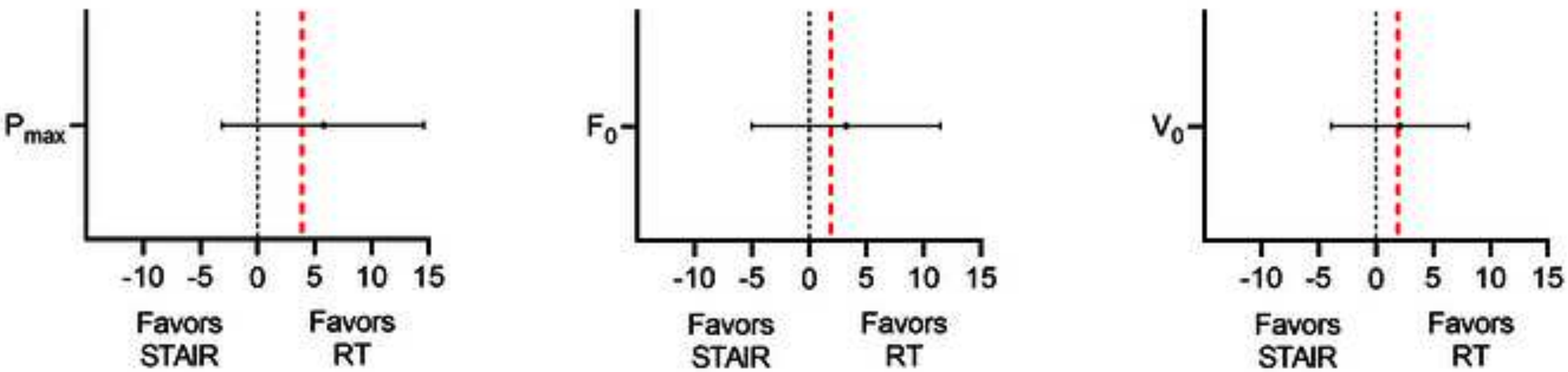


Table 1. Means ± SD for baseline characteristics of the subjects

Characteristic		RT (♂15;♀8)	STAIR (♂15;♀8)	p-value
Age (years)		70.7 ± 4.2	71.2 ± 4.5	0.722
Body height (cm)		168.4 ± 8.3	166.8 ± 8.7	0.534
Body mass (kg)		74.8 ± 11.6	72.9 ± 10.2	0.556
BMI (kg m^{-2})		26.4 ± 3.6	26.2 ± 3.4	0.908
Education (n)				0.335
	Primary education	0	1	
	Lower secondary education	3	0	
	Upper secondary education	4	5	
	Bachelor's or master's degree	16	17	
Chronic conditions (n)	Total number of chronic conditions	1.1 ± 1.1	0.8 ± 1.0	0.383[a]
	Hypercholesterolemia	6	1	
	Hypertension	8	3	
	Diabetes	2	1	
	(Rheumatoid) Arthritis	2	3	
	Thyroid problems	2	0	
	Gastro-intestinal problems	1	1	
	Cardiac arrhythmia	1	1	
	Kidney disease	0	1	
	Depression	0	2	

p-values of independent samples T-test or Mann-Whitney U test[a] for continuous variables and Chi-square tests for categorical variables; BMI = body mass index

Table 2. Training variables and progression for the resistance training (RT) and stair-climbing exercise (STAIR) program

	Focus	Exercise	Sets and repetitions	Load	Interset rest	Velocity
RT						
Week 1-4	Hypertrophy	Unilateral leg press	4 x 12-15	55% 1-RM	45s	2s ecc – 2s conc
Week 5-8	Power	Unilateral leg press	4 x 12	40% 1-RM	45s	2s ecc – maximal conc
Week 9-12	Power	Unilateral leg press	4 x 12	40% 1-RM + 10%	45s	2s ecc – maximal conc
STAIR						
Week 1-4	Hypertrophy	Forward step-up	4 x 12-15	Step height of 30-40cm, BM	45s	2s ecc – 2s conc
Week 5-8	Power	Stair climbing	4 x 2 flights of 6 stairs	BM	45s	Maximal
Week 9-12	Power	Stair climbing	4 x 2 flights of 6 stairs	BM + 10%	45s	Maximal

1-RM = one-repetition maximum; BM = body mass; ecc = eccentric; conc = concentric

Table 3. Estimated means and SE at baseline (pre-) and post-intervention test for functional capacity in the resistance training (RT) and the stair-climbing exercise (STAIR) group.

		RT		STAIR		P-values	
		Mean	SE	Mean	SE	Time	Time x group
Functional capacity							
10-m fast walk (s)	Pre	4.77	0.15	5.01	0.15		
	Post	4.41	0.15	4.52	0.15	**<0.001**	0.263
5xSTS duration (s)	Pre	8.51	0.28	8.28	0.28		
	Post	8.16	0.28	7.62	0.28	**<0.001**	0.197
5xSTS power (W)	Pre	305	16	290	16		
	Post	308	16	311*	16	**0.026**	0.087
6-step stair ascent duration (s)	Pre	1.92	0.11	1.86	0.11		
	Post	1.78*	0.11	1.59*	0.11	**<0.001**	**0.007**[a]
6-step stair ascent power (W)	Pre	581	42	552	42		
	Post	594	42	614*	42	**<0.001**	**0.035**
CMJ jump height (cm)	Pre	17.5	1.1	17.0	1.1		
	Post	18.7	1.1	18.5	1.1	**<0.001**	0.686

p-values of Linear Mixed-Effects Models analyses (significant values in bold); * significant within-group change from Pre to Post, [a]not normally distributed and non-parametric tests were performed and reported (Wilcoxon Signed Ranks for time effect; Mann-Whitney U test to compare percent changes from pre to post between groups for time x group effect). For easier interpretation, non-transformed data means were reported for all variables. STS = sit-to-stand; CMJ = countermovement jump. There were no baseline differences between groups.

Supplementary Table 1. Velocity (mean (SE)) in m s^{-1} (for leg press in RT and for stair ascent in STAIR) across the exercise sets and training weeks.

	Set	Week 6	Week 8	Week 10	Week 12	p-value for set	p-value for time
RT	1	0.580 (0.016)	0.582 (0.017)	0.579 (0.016)	0.580 (0.016)	< **0.001**[a]	0.699[a]
	2	0.586 (0.016)	0.609 (0.016)	0.582 (0.016)	0.586 (0.016)		
STAIR	1	0.629 (0.028)	0.666 (0.028)	0.626 (0.029)	0.623 (0.029)	**0.012**	**0.002**
	2	0.652 (0.028)	0.654 (0.029)	0.624 (0.029)	0.638 (0.029)		
	3	0.661 (0.029)	0.706 (0.028)	0.628 (0.028)	0.622 (0.029)		
	4	0.671 (0.028)	0.688 (0.028)	0.631 (0.028)	0.628 (0.030)		

p-values of Linear Mixed-Effects Models analyses for changes in velocity across sets and training weeks (significant values in bold); [a]not normally distributed and non-parametric tests were performed and reported (Wilcoxon Signed Ranks for effect of set or effect of time); p-values represent differences between the first and last set and between week 6 and week 12; RT = resistance training group, STAIR = stair-climbing exercise group. To note: for RT, only the velocity values of the right leg are reported.