J Musculoskelet Neuronal Interact 2022; 22(4):486-497

Journal of Musculoskeletal and Neuronal Interactions JMNI

Original Article

Effects of age on muscle power, postural control and functional capacity after short-term immobilization and retraining

Cecilia Elam[1†], Lars G. Hvid[2,3†], Ulrik Christensen[2], Michael Kjær[4,5], S. Peter Magnusson[4,5], Per Aagaard[2], Lina Bunketorp Käll[1,6‡], Charlotte Suetta[7,8,9‡]

[1]Department of Health and Rehabilitation, Institute of Neuroscience and Physiology, Sahlgrenska Academy, University of Gothenburg, Gothenburg, Sweden;
[2]Exercise Biology, Department of Public Health, Aarhus University, Denmark;
[3]The Danish MS Hospitals, Ry and Haslev, Denmark;
[4]Institute of Sports Medicine Copenhagen, Department of Orthopedic Surgery, Copenhagen University Hospital – Bispebjerg and Frederiksberg, Copenhagen, Denmark;
[5]Center for Healthy Aging, Department of Clinical Medicine, University of Copenhagen, Denmark;
[6]Centre for Advanced Reconstruction of Extremities (C.A.R.E.), Sahlgrenska University Hospital/Mölndal, Sweden;
[7]Geriatric Research Unit, Department of Geriatric and Palliative Medicine, Bispebjerg and-Frederiksberg Hospital - Copenhagen, Denmark;
[8]Geriatric Research Unit, Department of Medicine, Herlev and Gentofte Hospitals, Copenhagen, Denmark;
[9]CopenAge – Copenhagen Center for Clinical Age Research, University of Copenhagen, Denmark
[†]Shared 1[st] Authorship, [‡]Shared last Authorship

Abstract

Objectives: This study investigated the effect of lower limb immobilization and retraining on postural control and muscle power in healthy old and young men. **Methods**: Twenty men, nine old (OM:67.3±4.4 years) and eleven young (YM:24.4±1.6 years) underwent 2 weeks of unilateral whole-leg casting, followed by 4 weeks of retraining. Measures included center of pressure (CoP) sway length and area during single- and double-leg stance, maximal leg extensor muscle power, habitual and maximal 10-m gait speed, sit-to-stand performance, and 2-min step test. **Results**: After immobilization, leg extension muscle power decreased by 15% in OM (from 2.68±0.60 to 2.29±0.63 W/kg, $p<0.05$) and 17% in YM (4.37±0.76 to 3.63±0.69 W/kg, $p<0.05$). Double-leg CoP sway area increased by 45% in OM (218±82 to 317±145 mm^2; $p<0.05$), with no change in YM ($p=0.43$). Physical function did not change after immobilization but sit-to-stand performance (+20%, $p<0.05$) and 2-min step test (+28%, $p<0.05$) increased in OM following retraining. In both groups, all parameters returned to baseline levels after retraining. **Conclusion**: Two weeks of lower limb immobilization led to decreases in maximal muscle power in both young and old, whereas postural control was impaired selectively in old men. All parameters were restored in both groups after 4 weeks of resistance-based retraining.

Keywords: Aging, Balance, Disuse, Rehabilitation, Resistance Training

The authors have no conflict of interest.

Corresponding author: Charlotte Suetta, Geriatric Research Unit, Department of Geriatric and Palliative Medicine, Bispebjerg and-Frederiksberg Hospital - Copenhagen, Denmark
E-mail: charlotte.suetta@regionh.dk

Edited by: G. Lyritis
Accepted 17 June 2022

Introduction

Mantaining postural control and functional capacity at old age are crucial elements for an independent living[1]. Yet, it is well known that aging is associated with loss of muscle strength[2], muscle power[3], postural control[4], and a decline in physical function[2,5]. In addition, periods of muscle disuse leads to deteriorations in muscle function in individuals of all ages[6]. Due to a higher prevalence of acute and chronic diseases, older individuals are more at risk of sustaining periods of hospitalization and immobilization that increase the risk of developing additional deficits, often with significant consequences for the individual (i.e. quality of life) and the society (health care expenses)[7].

Although the loss of physical function and motor control with age is multifactorial[1,8], one of the major components is the remodelling process within the neuromuscular system, with loss of spinal motor neurons, denervation, formation of very large motor neurons and reduced number of especially type II muscle fibers[1,8]. These changes result in impaired mechanical muscle performance (reduced maximal muscle strength, power, and rate of force development [RFD]) along with impaired motor control[8,9]. Muscle strength and power are essential components for maintaining functional capacity at old age[2,5,10], especially movements involving the displacement of bodyweight such as stair climbing and rising from a chair[2,5]. Adequate levels of muscle power are also essential for preventing and counteracting perturbations in postural control[11] and thereby preventing falls[11].

Normal postural control entails a complex interaction between the musculoskeletal and neural systems, where the CNS generates muscle activity patterns to regulate the relationship between the centre of body mass and the base of support during static and dynamic gait and stance conditions[12,13]. Various visual, vestibular, somatosensory and musculoskeletal functions are critical components for supporting/ensuring postural control. Age, disease or injury-related declines in functioning of these systems are all likely to compromise physical function and postural control[13]. However, whether muscle power and postural control are affected by disuse in an age-dependant manner is not well known. Notably, recent data from Sarabon and Rosker demonstrated that a 14-day bed rest led to an impaired stabilizing function of the ankle muscles together with deteriorated postural reactive responses in older men[14]. Likewise, using a 14-day bed rest model, Rejc and colleagues[15] observed a 15% decline in maximal muscle power of the lower limb in older men (55–65 years), which was not reversed with 14 days of retraining, underlining the need for increased knowledge about how ageing affects muscle recovery.

During the last decade a number of studies[1,15-18], including some from our own group[2,19-21], have investigated how the effects of immobilization and bed rest on neuromuscular function and functional capacity are affected by age. We have previously investigated the effects of short-term (4 days) disuse and subsequent recovery (7 days) on lower limb muscle mechanical function in old vs. young individuals.21 Following 4-days disuse, lower limb mechanical muscle function (maximal muscle strength and rate of force development: RFD) were markedly impaired in both young and old males[21]. Notably, the 7-day recovery period was sufficient to restore muscle strength and RFD in young but not old individuals[21]. Additional experiments from our research group have addressed the influence of aging on changes in muscle activation, strength, RFD and skeletal muscle mass in old and young men in response to 2 week immobilization followed by 4 weeks of retraining[16]. In this extended time setting, old individuals demonstrated greater reductions in lower limb (knee extensor) muscle activation as a result of 2-week immobilisation, which was accompanied by a diminished capacity to restore muscle size and muscle architecture during the subsequent 4-week period of retraining compared to younger individuals[16].

Despite these research activities, a number of aspects have received little attention, including how age affects the ability to recover after a period of disuse, bed rest or immobilization. Moreover, most previous immobilisation and bed rest studies have focused on changes in myocellular signalling and maximal muscle strength whereas less is known about how lower-limb immobilization affects maximal muscle power, postural control and physical performance, with barely no knowledge existing about the effect of retraining on these aspects.

Consequently, the present study examined the effect of age on the changes in muscle power, postural control and physical function following 2 weeks of unilateral lower limb immobilization as well as 4 weeks of progressive resistance training. Since both muscle power[3,5,22] and postural control[4] are reduced at older age, and that age further affects the effects of immobilization and recovery[16,21], we hypothesized that older individuals would be more severely affected by immobilization compared to their young counterparts, and also recover at a slower rate. Further, we intended to examine, if 2 weeks of unilateral immobilization would translate into parallel deficits in locomotory performance, and to examine their pattern of recovery.

Methods

Participants and study design

Prior to study start, all participants underwent a medical examination by a physician, including a personal interview regarding drug use and measurement of blood pressure to screen for pathological conditions that could be exacerbated by the immobilization intervention. Only healthy and non-medicated individuals were included in the study. The level of physical activity was assessed prior to study onset using a validated questionnaire[23]. All participants were informed about the purpose, structure and possible risks of the study. The Ethics Committee (Copenhagen and Frederiksberg, Denmark) approved the conditions of the study (KF01–322606), and all experimental procedures were performed in accordance with the Declaration of Helsinki. Written, informed consent was obtained from all participants before inclusion in the study. The physical characteristics of the study population are presented in Table 1. While the present study reported longitudinal changes in lower extremity muscle power, postural control, and functional capacity, detailed information on the study design, sample size justification and additional data, have been published previously[16,19,24].

Table 1. Anthropometric characteristics and baseline test results of young men n=11 and old men n=8.

	Young (n=11)	Old (n=8)	*p*
Age (yrs)	24.4 1.6	67.3 ± 4.4	**<.001**
Weight (kg)	75.0 ± 7.5	86.2 ± 10.4	**.006**
Height (m)	1.81 ± 0.1	1.79 ± .1	.208
BMI (kg/m^2)	22.9 ± 1.7	27.0 ± 2.6	**.001**
Leg extensor power (W)	331.18 ± 55.2	250.11 ± 74.5	**.001**
Leg extensor power (W/kg)	4.37 ± 0.76	2.68 ± .60	**<.001**
Sway length *single-leg stance* (cm)	566.8 ± 98.7	1026.8 ± 194.7	0.055
Sway length *double-leg stance* (cm)	153 ± 70.2	204.8 ± 37.7	**<.001**
Sway area *single-leg stance* (mm^2)	1424.4 ± 279.4	3676.2 ± 805.1	**<.001**
Sway area *double-leg stance* (mm^2)	176.2 ± 94.9	217.9 ± 82	0.333
Gait speed *self-selected* (m/s)	1.38 ± .24	1.40 ± .25	0.800
Gait speed *maximum* (m/s)	2.44 ± .44	2.15 ± .34	0.160
Five-times sit-to stand test (s)	5.86 ± .66	7.66 ± 1.74	**0.023**
30-s sit-to-stand test (no)	26 ± 3.1	20.6 ± 7.4	**0.003**
2-min step test (no)	289.7 ± 60.6	213.3 ± 25.9	**0.002**

Data are given as mean (standard deviation). P-values<0.05 are presented in bold.

Experimental Procedures

All participants underwent familiarization experiments approximately 2 weeks prior to the testing procedures, after which the actual baseline assessment took place (Pre). Immediately after baseline testing, each participant was randomly assigned to have the right or left lower limb immobilized with a cast, while the non-immobilized leg was used as a control limb. All participants were submitted to 2 weeks of unilateral whole-leg casting. Following 2 weeks of immobilization, the cast was removed, and post-immobilization assessments were conducted (Imm), after which the participants took part in 4 weeks of unilateral progressive resistance training over a period of 4 weeks (more details given below). Subsequently, all test procedures were repeated at the end of the 4-week retraining period (Train). All test sessions were preceded by a short low-intensity warm-up on a stationary bicycle ergometer (5 min, 50-150 W).

Immobilization

Unilateral lower limb immobilization (random limb selection) was performed using a unilateral lower limb cast from the groin to the ankle with a 30° knee flexion (0°=full extension). The cast allowed mobility in the hip and ankle joints, and thus resulted in selective unloading of the knee extensor and flexor muscles. The participants were equipped with crutches and were carefully instructed not to engage in any weight bearing activities using the immobilized leg. Participants were allowed to perform free ambulation using the contralateral non-immobilized leg during the 2 weeks of immobilization. Immediately after removal of the cast all subjects received manual mobilization of the immobilized leg by a trained physitherapist to ensure full range of motion and to avoid pain during testing and retraining.

Retraining

The retraining program consisted of 4 weeks (3/week) of supervised progressive unilateral resistance training (*Train*) targeting the immobilized leg only. After a brief warm up on a stationary ergometer bike, all subjects performed three exercises for the lower limb (leg press; knee flexion and knee extension). The initial training load was estimated as described elsewhere[25], using a 5-repetition maximum (RM) test, and was adjusted weekly. During the first week of retraining, each session consisted of 4 sets of 12 repetitions at 15 RM loads, whereas the second and third weeks involved 5 sets of 10 repetitions using 12 RM loads while the 4th week comprised 4 sets of 10 repetitions at 12 RM loading intensity.

Measures

Leg extension power

Maximal unilateral leg extension power was measured using the Nottingham Power Rig[22], and expressed in Watts (W) and normalized to body weight (i.e. W/kg). The horisontal position of the seat was adjusted to allow a knee angle of 15° with the footplate being fully pushed down. Seat position was measured to ensure the same seat setting across test sessions. During testing, participants were seated with their arms folded over the chest and the upper body leaning slightly backwards. One foot was placed on the pedal attached to the flywheel while the other foot rested on the floor. After performing 2 to 3 warm-up trials, the participants were instructed to push the pedal forward as hard and fast as possible. Verbal instruction and visual on-line feedback of exerted power were standardized to optimize test reliability. Measurements were repeated until no further improvement in peak power of 2 consecutive tests could be observed, using a minimum of five trials. The rest period between successive trials was set to 30 seconds. The order of leg tested was determined by randomization. Measurement of maximal leg extensor muscle power using the Nottingham Power Rig has previously been validated and considered to be safe in old and very old individuals[10].

Postural control

Postural sway analysis was performed with the participants standing still on a force plate (AMTI OR6-5-1000; Advanced Mechanical Technology Inc., MA, USA). The force plate was connected to a computer to which the vertical ground reaction force (*Fz*) and force moments (*Mx, My*) could be collected using an external 16-bit A/D converter. All signals were synchronously sampled at 100 Hz A/D conversion rate. During later off-line analysis, all force plate signals (*Fz, Mx, My*) were lowpass filtered using a 4^{th} order zero-lag Butterworth filter with a cutoff frequency of 8 Hz[26], following which the trajectory of the center of Pressure (*CoP*) was calculated ($x=x_o+My/Fz$, $y=y_o+Mx/Fz$; with $[x_o, y_o]$ representing the geometrical center of the force plate surface). CoP sway velocity ($mm \cdot min^{-1}$) and total CoP sway area (mm^2) were also calculated. During testing, participants were instructed to stand as still as possible for 15 seconds with their eyes open, and arms freely hanging along the side with their feet together (double-leg stance) in a Romberg test position for balance[27], followed by single-leg stance test without hand support (SOLEO)[28]. In addition, participants were instructed to focus visually on a circle placed at eye level 2.5 meters away. All participants performed a few practice trials prior to the test trials, and all sampling gait speed were started when the participants had settled in a stable and safe position. The participants had to maintain balance for 15 seconds in three sampling trials in each stance position. CoP sway length and area during the single-leg and double-leg stance tasks were identified from the trials with the shortest sway length and used for analyses.

Horizontal gait speed

Gait speed was measured over a 10-m straight walking course[29]. From a standing position, the participants were asked to first walk 10 m at their habitual walking pace (best of 2 trials) followed by walking 10 m at their maximal walking pace (best of 2 trials), without running and continue further than 10 m to avoid stopping or decelerate before reaching the 10 m mark[29,30]. No verbal encouragement was given during this test. The time was measured with a stopwatch to the nearest 0.1 s. Gait speed (maximal and habitual) was computed as the 10-m distance divided by the elapsed time (m/s).

Sit-to stand performance

Sit-to-stand performance was measured as (i) the number of times a person was able to rise and sit from a standardized chair within 30 s (30-s sit-to-stand test)[31] and (ii) by use of the Five-Times sit-to-stand test[27]. During both tests, the participant was seated in the middle of a standardized chair (with no arm rest, seat height 45 cm) back straight and arms crossed against the chest. At the signal 'go', participants were instructed to rise to a full stand (body erect and straight) and then immediately return to the initial seated position. During the 30-s sit-to-stand test participants were encouraged to complete as many full stands as possible within 30 s and were carefully instructed and monitored to fully sit between each stand. The total number of stands within 30 s was measured[32]. During the five-times sit-to-stand test the time it took the participant to rise five times from the standardized chair was measured to the nearest second[27].

Step performance

Lower limb muscle endurance was evaluated using the 2-minute high knee raises test, also referred to as the 2 minute step test (2-min step test), which is an integral part of the Senior Fitness Test[28]. Normative Senior Fitness Test data have previously been presented for an American population[33], and is shown to compare well with Scandinavian age-matched adults[34]. In brief, the test subject stands up straight next to a wall while a mark is placed on the wall at the level corresponding to midway between the patella (knee cap) and illiac crest (top of the hip bone). On the "go" signal the subject begins stepping in place for 2 minutes, raising each knee to the height of the mark on the wall, for as many times as possible. In the present study, a modified version of the 2-min step test was used, namely, the number of times both the right and left knee reaches the required height was counted, instead of the right knee only.

Statistical analysis

Independent sample T-test was used to analyze between-group differences at baseline. Paired t-testing was used to evaluate within-group differences from pre-immobilization (*Pre*) to post-immobilization (*Imm*), from post-immobilization to post-retraining (*Train*) and from Pre to Train. Differences between YM and OM with respect to the outcome of the 2-week immobilization period were analyzed in terms of change from baseline (Pre) to after immobilization (Imm). Differences between YM and OM with respect to retraining was analyzed in terms of change from the assessment after immobilization (Imm) to the assessment after the retraining period (Train). Because baseline characteristics were unbalanced at baseline, analyses of covariance (ANCOVA) were done with baseline values as a covariate. Thus, change from Pre to Imm and from Imm to Train in each outcome measure was used as a dependent variable, initial score of each outcome measure

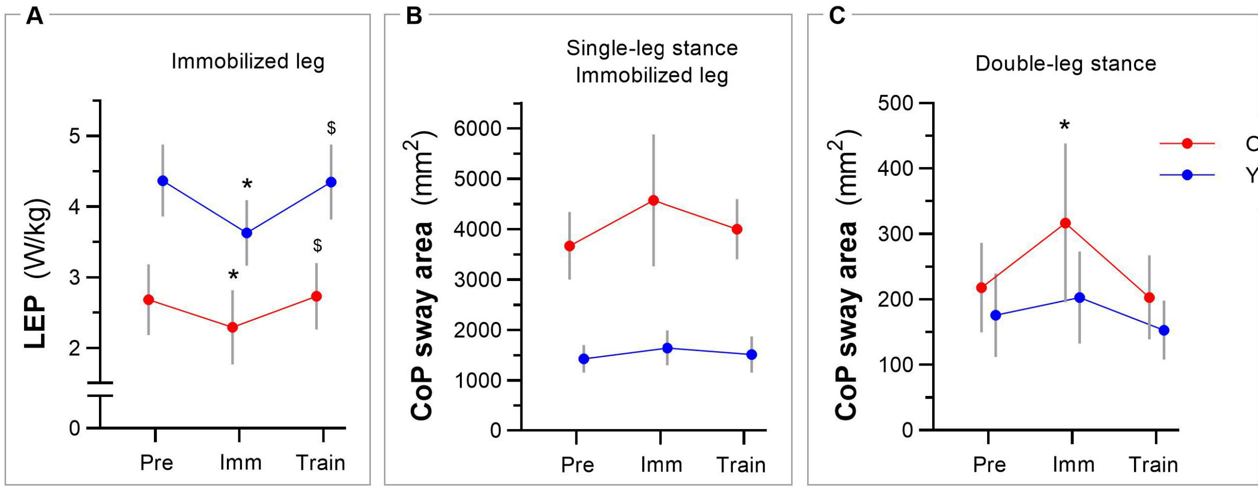

Figure 1. (**A**) Maximal leg extensor muscle power and CoP sway area during (**B**) single-leg and (**C**) double-leg stance obtained at baseline (Pre), after 2 weeks unilateral lower limb immobilization (Imm) and following 4 weeks retraining (Train) in young and old men. * Imm vs. Pre (p<0.05), $ Train vs. Imm (p<0.05).

as a covariate, and intervention group as factor.

To explore the potential association between longitudinal changes in leg extension muscle power, physical function and postural control, correlation analysis on the relative change (%) from Pre to Imm and from Imm to Train for each measure was performed using the Pearson product-moment method. Further, Pearson correlation analysis was performed to examine the potential relationship between maximal muscle power (normalized to body mass) and functional capacity/postural control at baseline. Since the functional capacity outcome measures were conducted on both legs, we used the mean baseline leg extension power for the immobilized AND control leg in the analyses. The results of the correlation analyses were presented for each group in separate, and for both groups combined. All statistical analysis was performed in SPSS v.25.0 (IBM Corp., Armonk, NY, USA). All data are expressed as mean ± SD unless otherwise stated, with the significance level set to p≤0.05 (two-tailed).

Results

Twenty healthy men, 11 young (YM: 24.4±1.6 yrs) and 9 old (OM: 67.3±4.4 yrs) volunteered to participate in the study and completed the immobilization and retraining period. One OM was excluded at baseline for reasons not related to the study. The results of the questionnaire survey showed that the two groups were comparable in terms of physical activity levels (OM: 5.2±1.4 h/week; YM: 5.0±0.9 h/week), with no between-group differences observed for the engagement in low-to-moderate intensity activities.

Baseline comparisons

At baseline, OM were heavier and had larger BMI than YM (Table 1). OM differed from YM in terms of muscle power and postural control as reflected by lower leg extension power (OM: 2.68±0.60 W/kg; YM 4.37±0.76 W/kg; p<0.05) and greater CoP sway length during double-leg stance (OM: 204.7±37.7 cm; YM 153.0±70.1 cm, p<0.05) along with a tendency for greater CoP excursion during single-leg stance compared to YM (OM: 1026.8±194.6 cm; YM 566.7±98.6 cm, p=0.06). Likewise, CoP sway area during single-leg stance was greater in OM than YM (OM: 3676±805 mm^2; YM 1424±279 mm^2; p<0.05) although not different between OM and YM during double-leg stance (Table 1). Also, OM performed worse compared to YM in the five-times sit-to stand test (OM: 7.6±1.7 s; YM 5.8±0.6 s; p<0.05), in the 30-sec sit-to-stand test (OM: 20.6±7.3; YM 26.0±3.1 sit-to-stands; p<0.05), and in the 2-min step test (OM: 213±25; YM 289±60 leg lifts; p<0.05) (Table 1). In contrast, YM and OM did not differ in habitual or maximal gait speed at baseline (Table 1).

Effects of immobilization

Following immobilization, leg extension muscle power decreased by 15% in OM (2.68±0.60 to 2.29±0.63 W/kg) and 17% in YM (4.37±0.76 to 3.63±0.69 W/kg) (p<0.05) (Table 2 and Figure 1). Postural control was negatively affected in OM reflected by a 45% increase in CoP sway area during double-leg stance (217±82 to 317±145 mm^2; p<0.05) (Table 2 and Figure 1) along with trends toward increases in single-limb sway CoP area (3676±805 to

Table 2. Unilateral leg extension power and postural control (center of pressure sway length and sway area) assessed in young and old men at at baseline (Pre), after 2 weeks unilateral lower limb immobilization (Imm) and following 4 weeks retraining (Train) in young and old men.

	Pre	Imm	Change from Pre to Imm	*p*	Train	Change from Imm to Train	*p*
	Mean (SD)	Mean (SD)	Mean (95%CI)		Mean (SD)	Mean (95%CI)	
Leg extensor power (W/kg)							
Young (n=11)	4.37 ± 0.76	3.63 ± 0.69	-0.75 (-0.95 to -0.54)	**.001**	4.35 ± 0.79	0.72 (0.33 to 1.10)	**<.001**
Old (n=8)	2.68 ± 0.60†	2.29 ± 0.63	-.39 (-0.81 to -0.10)	**.018**	2.73 ± 0.56	0.44 (0.20 to 0.67)	**.003**
Young vs Old			*p*=.860 (η_p^2= 0.002)			*p*=.372 (η_p^2= 0.050)	
Sway length *single-leg* (cm)							
Young (n=11)	566.8 ± 98.7	564.3 ± 107.2)	-2.5 (-71.3 to 66.4)	.938	521.6 ± 98.0	-42.7 (-96.8 to 11.5)	.110
Old (n=8)	1026.8 ± 194.7†	1187.3 ± 247.8	160.5 (-17.9 to 338.9)	.071	1124.5 ± 130.0	-62.8 (-232.9 to 107.3)	.412
Young vs Old			***p*=.036** (η_p^2= 0.246)			*p*=.216 (η_p^2= 0.094)	
Sway length *double-leg* (cm)							
Young (n=11)	153.0 ± 70.2	137.6 ± 27.3	-15.2 (-60.2 to 29.9)	.470	124.7 ± 30.5	-13.2 (-38.5 to 12.2)	.931
Old (n=8)	204.8 ± 37.7	205.8 ± 45.4	1.06 (-26.8 to 28.9)	.275	189.1 ± 38.9	-16.7 (-53.0 to 19.6)	.313
Young vs Old			***p*=.006** (η_p^2= 0.391)			*p*=.988 (η_p^2= 0.000)	
Sway area *single-leg* (mm²)							
Young (n=10)	1424.4 ± 379.4	1640.9 ± 486.0	216.5 (-76.9 to 510.0)	.129	1509.1 ± 503.2	-131.8 (-447.5 to 184.0)	.370
Old (n=8)	3676.2 ± 805.1†	4570.7 ± 1566.0	894.5 (-181.3 to 1970.2)	.090	3997.3 ± 714.4	-573.4 (-1643.5 to 496.7)	.246
Young vs Old			*p*=.542 (η_p^2= 0.025)			*p*=.400 (η_p^2= 0.048)	
Sway area *double-leg* (mm²)							
Young (n=11)	176.2 ± 94.9	202.9 ± 104.9	26.6 (-46.2 to 99.4)	.429	153.2 ± 66.8	-49.7 (-129.5 to 30.1)	.193
Old (n=8)	217.9 ± 82.0	317.0 ± 145.2	99.1 (7.2 to 191.0)	**.038**	203.2 ± 76.85	-113.8 (-232.3 to 4.7)	.057
Young vs Old			*p*=.136 (η_p^2= 0.142)			*p*=.471 (η_p^2= 0.035)	

Changes are presented as mean (95% Confidence Interval [CI]), p-values<0.05 are presented in bold, †= different from Young (p<0.05), η_p^2=partial eta-squared (effect size).

4570±1565 mm² [+24%]; p=0.09) (Table 2 and Figure 1) and single-leg sway length (1026.8±194.7 to 1187.3±247.8 cm [+16%]; p=0.07). In contrast, postural control remained unaffected in YM leading to a between-group difference in single-leg sway length (p=0.036). Sway length during bilateral stand was somewhat reduced in YM and rather unaffected in OM, resulting in a between group-difference (p=0.006) with respect to change from baseline to after immobilisation. Apart from trends towards a decrease in 2-min step test (p=0.06) in OM and a decrease in maximal gait speed in both YM (p=0.08) and OM (p=0.10) (Table 3), there were no changes in physical function following immobilization (Table 3).

Effects of retraining

Following four weeks of resistance training, leg extension muscle power of the immobilized leg increased by 17% in YM (3.63±0.69 W/kg vs 4.35±0.79 W/kg) and 16% in OM (2.29±0.63 W/kg vs 2.73±0.56 W/kg), respectively (p<0.05) (Table 2 and Figure 1). Despite a trend (p=0.057) for CoP sway area to decrease following retraining in OM during double-leg stance (36%; from 317.0±145.1 to 203.0±76.8 mm²) (Table 2 and Figure 1), changes in CoP sway parameters following retraining generally failed to reach statistical significance. In terms of functional capacity, OM demonstrated increases in five-times sit-to-stand test performance (+20%, p<0.05) and the 2-min step test (+28%, p<0.05), respectively (Table 3).

Correlation analysis

No associations were observed between longitudinal changes (%) in leg extension muscle power for the immobilized leg vs. changes in postural control or functional capacity, respectively, from Pre to Imm or from Imm to Train (Table 4a and b). When analyzing both groups separately, with respect to the correlation between baseline (pre-immobilisation) leg extension power in the immobilized leg versus postural stability control (Sway Length and Sway Area), no significant correlation was shown (Table 5a), whereas for the groups

Table 3. Functional capacity (horizontal gait speed, five-time sit-to-stand test, 2-min step test) assessed in young and old men at at baseline (Pre), after 2 weeks unilateral lower limb immobilization (Imm) and following 4 weeks retraining (Train) in young and old men.

	Pre	Imm	Change from Pre to Post	*p*	Train	Change from Imm to Train	*p*
	Mean (SD)	Mean (SD)	Mean(95%CI)		Mean (SD)	Mean(95%CI)	
Gait Speed *self-selected* (m/s)							
Young (n=11)	1.38 ± 0.24	1.37 ± 0.24	-0.01 (-0.13 to 0.11)	.866	1.42 ± 0.26	0.05 (-0.06 to 0.16)	.333
Old (n=8)	1.40 ± 0.25	1.39 ± 0.26	-0.01 (-0.14 to 0.12)	.829	1.45 ± 0.17	0.06 (1.20 to 1.59)	.284
Young vs Old			*p*=.969 (η_p^2= 0.000)			*p*=.954 (η_p^2= 0.000)	
Gait Speed *maximum* (m/s)							
Young (n=11)	2.44 ± 0.44	2.30 ± 0.47	-0.13 (-0.30 to 0.03)	.097	2.27 ± 0.45	-0.03 (-0.38 to 0.32)	.865
Old (n=8)	2.15 ± 0.34	1.99 ± 0.35	-0.17 (-0.36 to 0.03)	.082	2.08 ± 0.45	0.09 (-0.19 to 0.37)	.473
Young vs Old			*p*=.583 (η_p^2= 0.019)			*p*=.645 (η_p^2= 0.014)	
Five-times sit-to-stand test (s)							
Young (n=11)	5.86 ± 0.66	5.71 ± 0.93	-0.15 (-0.55 to 0.25)	.410	5.25 ± 0.73	-0.45 (-1.28 to 0.28)	.250
Old (n=8)	7.66 ± 1.74†	8.19 ± 3.20	0.53 (-1.14 to 2.19)	.479	6.58 ± 2.07¥	-1.61 (-3.10 to -0.12)	**.037**
Young vs Old			*p*=.848 (η_p^2= 0.002)			*p*=.970 (η_p^2= 0.000)	
30-s sit-to-stand test (no)							
Young (n=11)	26.0 ± 3.1	26.2 ± 4.0	0.2 (-1.4 to 1.7)	.800	28.9 ± 3.3	2.7 (-0.5 to 5.9)	.086
Old (n=8)	20.6 ± 7.4†	20.6 ± 5.5	0.0 (-4.0 to 4.0)	1.000	22.8 ± 5.5	2.1 (-0.2 to 4.5)	.069
Young vs Old			*p*=.348 (η_p^2= 0.055)			***p*=.022** (η_p^2= 0.286)	
2-min step test (no)							
Young (n=11)	290 ± 61	270 ± 81	-20 (-46 to 7)	.135	299 ± 55	28 (-9 to 66)	.122
Old (n=8)	213 ± 26†	167 ± 57	-46 (-95 to 3)	.063	214 ± 40	46 (9 to 83)	**.021**
Young vs Old			*p*=.511 (η_p^2= 0.027)			*p*=.975 (η_p^2= 0.000)	

Difference between young and old men with respect to the various outcome measures collected at the three timepoints (Pre, Imm and Train) were analyzed using analyses of covariance (ANCOVA) with change in each outcome measure as a dependent variable, initial score of each outcome measure as a covariate, and intervention group as factor. P-values<0.05 presented in bold, † = different from Young (p<0.05), ¥ = different from pre-test (p<0.05), η_p^2= partial eta-squared (effect size).

Table 4a. Correlation analysis on longitudinal changes (%) from pre-immobilization (Pre) to post-immobilization (Imm) in leg extension power in the immobilized leg versus changes in postural control parameters assessed during quiet standing on two feet (sway length and sway area) and functional capacity variables.

Variable	Young (n=11)		Old (n=8)		Young & Old collapsed (n=19)	
	r	*p*	r	*p*	r	*p*
Postural control variables						
Sway length - *single-leg stance*	.07	.83	-.17	.92	.15	.55
Sway length - *double-leg stance*	-.18	.62	.03	.95	.25	.31
Sway area - *single-leg stance*	.17	.64	-.17	.68	.15	.55
Sway area - *double-leg stance*	-.18	.62	.03	.95	.02	.94
Functional capacity variables						
Gait speed – *self-selected (m/sec)*	-.08	.81	-.13	.76	.02	.93
Gait speed – *maximum (m/sec)*	-.22	.51	-.45	.27	-.25	.31
Five-times sit-to-stand test *(sec)*	-.28	.40	-.01	.97	.02	.93
30-sec sit-to-stand test *(n)*	-.02	.95	.31	.46	.14	.56
2-min step test *(n)*	.30	.38	.34	.40	.12	.63

Presented in the table are Pearson correlation coefficient with corresponding p-value. P-values<0.05 were considered significant.

Table 4b. Correlation analysis on longitudinal changes (%) from post-immobilization (Imm) to post re-training (Train) in leg extension power in the immobilized leg versus changes in postural control parameters assessed during quiet standing on two feet (sway length and sway area) and functional capacity variables.

Variable	Young (n=11)		Old (n=8)		Young & Old collapsed (n=19)	
	r	*p*	r	*p*	r	*p*
Postural control variables						
Sway length - *single-leg stance*	-.29	.39	.04	.92	-.13	.60
Sway length - *double-leg stance*	.06	.87	-.06	.89	.02	.95
Sway area - *single-leg stance*	.001	1.00	.06	.88	.03	.92
Sway area - *double-leg stance*	.08	.83	-.03	.95	.04	.88
Functional capacity variables						
Gait speed – *self-selected (m/sec)*	-.20	.55	-.10	.81	-.17	.48
Gait speed – *maximum (m/sec)*	-.27	.43	-.32	.44	-.28	.24
Five-times sit-to-stand test *(sec)*	-.11	.74	-.22	.60	-.14	.56
30-sec sit-to-stand test *(n)*	.20	.56	-.12	.78	.10	.69
2-min step test *(n)*	.05	.88	-.09	.83	-.01	.98

Presented in the table are Pearson correlation coefficient with corresponding p-value. P-values<0.05 were considered significant.

Table 5a. Correlation analysis on baseline (pre-immobilisation) leg extension power in the immobilized leg versus postural control parameters (sway length and sway area).

Variable	Young (n=11)		Old (n=8)		Young & Old collapsed (n=19)	
	r	*p*	r	*p*	r	*p*
Postural control variables						
Sway length - *single-leg stance*	-.22	.51	-.36	.39	-.76	**<.001**
Sway length - *double-leg stance*	-.06	.87	.01	.97	-.35	.14
Sway area - *single-leg stance*	.23	.53	-.18	.68	-.71	.001
Sway area - *double-leg stance*	.44	.21	.07	.87	-.01	.96

Presented in the table are Pearson correlation coefficient with corresponding p-value. P-values<0.05 were considered significant and are presented in bold.

Table 5b. Correlation analysis on mean baseline leg extension power for the immobilized AND control leg versus functional capacity variables (gait-speed, sit-to-stand test and 2-min step test).

Variable	Young (n=11)		Old (n=8)		Young & Old collapsed (n=19)	
	r	*p*	r	*p*	r	*p*
Functional capacity variables						
Gait speed – *self-selected (m/sec)*	-.10	.76	.25	.55	.07	.78
Gait speed – *maximum (m/sec)*	-.06	.86	.07	.87	-.27	.27
Five times sit-to-stand test *(sec)*	-.56	.07	.32	.44	-.48	**.04**
30-sec sit-to-stand test *(n)*	.45	.16	-.06	.89	.63	**.004**
2-min step test *(n)*	-.21	.54	-.45	.27	.39	.10

Presented in the table are Pearson correlation coefficient with corresponding p-value. P-values<0.05 were considered significant and are presented in bold.

collapsed, significant correlations were shown for leg extension power in the immobilized leg and sway length and sway area of the immobilized leg (p<.001 for both). Similarily, when analyzing both groups separately, no significant correlation was shown between mean baseline leg extension power for the immobilized AND control leg versus functional capacity variables (Gait-speed, 30s sit-to-stand test, five-times sit-to-stand test, 2-min step test) (Table 5b), whereas for the groups collapsed, significant correlations were shown for 30s as well as five-times sit-to-stand tests (p=0.04 and p=0.004, respectively).

Discussion

The main finding of the present study was that two weeks of unilateral lower limb immobilization resulted in marked declines in maximal leg extensor power in both young (-17%) and older (-15%) men, along with an increase in double-leg stance postural CoP sway area in older men. Moreover, sway length increased more in old compared to young men. In contrast, physical performance was not affected by the period of unilateral immobilization, apart from trends towards decreases in maximal gait speed (young and old) and a decrease in the step test endurance capacity in old men. Notably, four weeks of supervised resistance-based retraining fully reversed leg extension power and postural control in both young and old men, along with increases in Sit-to-Stand performance and maximal gait speed in older men.

Age-related changes in lower limb muscle function

The included young and old subjects were healthy, recreationally active men within the normal range of anthropometric characteristics (weight, height and BMI) and physical function (leg extension muscle power, gaitspeed and sit-to-stand performance), for young and old, respectively[2] and notably, there was no difference in the level of habitual physical activity between the groups. Yet, older men demonstrated a 25% deficit in leg extension muscle power compared to their younger counterparts at baseline, which was further aggrevated when normalized to bodyweight (39% deficit), in line with previous results in larger cohorts of men and women across the age-span[2,5,35]. As expected, age-related differences at baseline primarily were observed in test conditions requiring high muscle power and/or postural motor control (leg extension muscle power, 30s-sit-to-stand performance, CoP sway area/length), in contrast to habitual gait speed that did not differ between young and old. In line with previous observations[4], the age-related differences in postural control were most evident during single-leg assessments. Specifically, older men demonstrated larger single-leg stance sway area (+158%) and sway length (+81%), compared to young, whereas the differences were less manifested during double leg-stance sway testing, where CoP excursion was found to be elevated in old (+34%) compared to young men.

Effects of immobilization

Following 2 weeks of immobilization, significant increases in CoP sway area were observed during double-leg stance in OM (+46%) along with tendencies (p=0.07–0.09) towards increases in single leg sway length (+16) and sway area (+24%). Only a few studies have investigated the combined effect of age and immobilization/bed rest on postural control[14], with Sarabon and colleagues reporting somewhat comparable results in terms of postural control in older adults following 2-week bed rest[14]. The negative impact of immobilization on postural control in a large part may be explained by the detrimental effect of lower limb immobilization on neuromuscular function[36]. In fact, we and others have previously demonstrated that neuromuscular function as estimated by measurements of quadriceps femoris activation and rapid force capacity[19] and mechanical muscle performance during fast contractions of the knee extensors[37] are more severely affected by short-term immobiliztion in old compared to young individuals. Yet, muscle power decreased to a similar degree in both young and old in the present study, as also observed by Rejc et al. when assessing changes in maximal lower limb muscle power in young (18–30 yrs) and older (55–65 yrs) adults after 2 weeks of bed-rest[15]. The lack of age-specific changes in muscle power could rely on a smaller sensitivity in the assessment of maximal leg extension muscle power compared to the assessment of rapid force capacity (rate of force development: RFD).

In contrast, the negative impact of lower limb immobilization on postural control was selectively affecting the group of older men, which at least in part may be explained by the age-related reduction in maximal lower limb muscle power at baseline that was further reduced in response to two weeks immobilization. Notably, physical function was not affected to any major extent by the period of immobilization although trends (p=0.06–0.09) towards a decrease in maximal gait speed (YM, OM) and Step Test endurance (OM) were noted. These observations may indicate that the present bilateral tests of functional performance (gait speed, sit-to-stand performance and step test) were not as sensitive to the regimen of unilateral lower limb immobilization as the assessment of single-limb leg extensor muscle power and postural control.

Effects of retraining

In the present study, resistance training was specifically chosen as to facilitate restoration of muscle function since it represents a well-known strategy that effectively increases muscle mass and neuromuscular performance (e.g., causing gains in muscle strength, rate of force development and maximal muscle power)[1,38,39]. Notably, the responses to retraining reported in the literature, especially in old individuals, vary to a large degree depending on the type and length of exercise intervention[14-16,19,30], as well as the investigated strength/power/functional parameters. In the present study, four weeks of resistance retraining appeared effective to restore pre intervention levels of muscle power in both young and old men. In contrast, Reic et al. found that 2 weeks of mixed retraining (six sessions in total, including resistance training) following 2 weeks of bed rest was sufficient to restore muscle power in young but not old men[15]. In the study by Rejc et al. however, the retraining program had the same duration as the disuse period (14 days), which may not be long enough to completely reverse muscle power in old participants. These observations are supported by previous data from our own group demonstrating that older adults have a slower recovery in neuromuscular function and contractile capacity following short-term (2 week) immobilization compared to young individuals[16,19]. Specifically, four weeks of progressive resistance based retraining subsequent to two weeks unilateral lower limb immobilization caused full recovery of muscle mass and rapid force capacity (RFD) in young but not older individuals[19,24]. Notably, in the present study old men showed gains in functional capacity with retraining manifested by significant improvements in five-times sit-to-stand test and the 2-min step test, which were not observed in young men, the latter likely due to a ceiling effect.

It is worth noting that proprioception plays an essential role in balance control, and that in humans, adequate postural control during standing requires continuous calf muscle activity[40]. In the present study, both hip extensor and knee extensor muscles as well as plantar flexors were targeted by the resistance exercises performed, which included multi-joint leg press training documented to stimulate neuromuscular function in both the leg extensors and plantar flexors[41,42]. Notably, previous reports have indicated a linkage between maximal knee extensor strength and risk of falling in elderly adults with osteoarthritis[43], which further indicates the involvement of the knee extensor musculature in postural control. Importantly however, the findings of the present study indicate that in terms of muscle power, postural control and functional capacity, four weeks of active retraining involving high-intensity muscle actions (i.e. heavy-resistance strength training) appears effective of reversing the negative effect of short-term (2 week) immobilization in both young and old adults.

Correlation analyses

Even though the benefits of resistance exercise intervention on muscle power and functional capacity in acute hospitalized older adults have been demonstrated[44], the results of the present study (i.e., no statistically significant correlations) did not support that immobilization-induced declines or subsequent training-induced gains in leg extensor power were directly linked to concurrent improvements in postural balance or in functional capacity, respectively. Neither could leg extensor power be linked to postural control or functional capacity variables at baseline. It is likely that multiple factors may have acted synergistically, directly or indirectly, to contribute to the increments in post-retraining test scores presently observed across young and old age groups.

Study limitations

A number of potential limitations may be mentioned for the present study. Firstly, the study only included healthy adult men. The results should therefore only cautiously be extrapolated to other populations, such as individuals with pathological conditions or frail older adults. However, results from the study may still expand our understanding of the mechanisms and range of impairment associated with the loss in muscle function and postural control following disuse, which may be helpful for the development of effective therapeutic approaches in old adults. Such approaches would be expected to help reduce the risk of functional deterioration in aging individuals that may have long-lasting negative effects on quality of life and eventually linkages to mortality. Secondly, insufficient postural control and falls often occur in dynamic situations[45], which imply that static sway CoP metrics as used in the present study may not be optimal in predicting future falls. Finally, even though numerous differences in the present study approached statistical significance, the absence of significant between-group differences were plausible due to low statistical power (i.e., small sample size).

Conclusions

In conclusion, the present findings demonstrate that two weeks of lower limb immobilization leads to reduced leg extensor power in both young and old men, whereas impairments in postural control only were observed in old adults. Tendencies were observed for impaired performance during bilateral motor tasks including assessments of maximal gait speed (young and old) and 2-min step test endurance (old). Importantly, four weeks of progressive resistance training effectively restored lower limb muscle power and postural control in both young and old men.

Funding

This research was funded by the Danish National Research Council, the Danish Rheumatology Association, Faculty of Health Sciences, University of Copenhagen, the Danish Ministry of Culture and the Swedish Foundation for Rehabilitation and Medical science.

Acknowledgement

The authors would like to express their gratitude to the study participants for their time and effort.

Authors' contributions

LGH, UC, MK, PAA, SPM and CS conceived and designed the study. LGH, UC and CS performed the experiments. CE, LGH and LBK analyzed data. CE, LGH, LBK, PAA, PM, MK and CS interpreted results. CE, LBK, LGH, PAA and CS drafted the manuscript. All authors edited and approved the final version of the manuscript.

References

1. Aagaard P, Suetta C, Caserotti P, et al. Role of the nervous system in sarcopenia and muscle atrophy with

aging: strength training as a countermeasure. Scand J Med Sci Sports 2010;20:(1):49-64.

2. Suetta C, Haddock B, Alcazar J, et al. The Copenhagen Sarcopenia Study: lean mass, strength, power, and physical function in a Danish cohort aged 20–93 years. J cachexia, sarcopenia muscle 2019;10:(6):1316-29.
3. Alcazar J, Kamper RS, Aagaard P, et al. Relation between leg extension power and 30-s sit-to-stand muscle power in older adults: validation and translation to functional performance. Sci Rep 2020;10:(1):1-8.
4. Du Pasquier R, Blanc Y, Sinnreich M, et al. The effect of aging on postural stability: a cross sectional and longitudinal study. Neurophysiologie Clin 2003; 33:(5):213-8.
5. Alcazar J, Aagaard P, Haddock B, et al. Age-and sex-specific changes in lower-limb muscle power throughout the lifespan. J Gerontol A Biol Sci Med Sci 2020; 75(7):1369-1378
6. Campbell M, Varley-Campbell J, Fulford J, et al. Effect of immobilisation on neuromuscular function *in vivo* in humans: a systematic review. Sports Med 2019; 49:(6):931-50.
7. Gillis A, MacDonald B. Deconditioning in the hospitalized elderly. Can Nurse 2005;101:(6):16.
8. Hunter SK, Pereira HM, Keenan KG. The aging neuromuscular system and motor performance. J Appl Physiol 2016;121:(4):982-95.
9. Enoka RM, Christou EA, Hunter SK, et al. Mechanisms that contribute to differences in motor performance between young and old adults. J Electromyogr Kinesiol 2003;13:(1):1-12.
10. Bassey EJ, Fiatarone MA, O'neill EF, et al. Leg extensor power and functional performance in very old men and women. Clin Sci 1992;82:(3):321-7.
11. Skelton DA, Kennedy J, Rutherford OM. Explosive power and asymmetry in leg muscle function in frequent fallers and non-fallers aged over 65. Age Ageing 2002; 31:(2):119-25.
12. Maki BE, McIlroy WE. Postural control in the older adult. Clin Geriatr Med 1996;12:(4):635-58.
13. Paillard T. Relationship between muscle function, muscle typology and postural performance according to different postural conditions in young and older adults. Front Physiol 2017;8:(585.
14. Sarabon N, Rosker J. Effect of 14 days of bed rest in older adults on parameters of the body sway and on the local ankle function. J Electromyogr Kinesiol 2013;23:(6):1505-11.
15. Rejc E, Floreani M, Taboga P, et al. Loss of maximal explosive power of lower limbs after 2 weeks of disuse and incomplete recovery after retraining in older adults. J Physiol 2018;596:(4):647-65.
16. Suetta C, Hvid LG, Justesen L, et al. Effects of aging on human skeletal muscle after immobilization and retraining. J Appl Physiol 2009;107:(4):1172-80.
17. Dideriksen K, Boesen A, Kristiansen J, et al. Skeletal muscle adaptation to immobilization and subsequent retraining in elderly men: no effect of anti-inflammatory medication. Exp Gerontol 2016;82:(8-18.
18. Vigelsø A, Gram M, Wiuff C, et al. Six weeks' aerobic retraining after two weeks' immobilization restores leg lean mass and aerobic capacity but does not fully rehabilitate leg strength in young and older men. J Rehabil Med 2015;47:(6):552-60.
19. Hvid L, Aagaard P, Justesen L, et al. Effects of aging on muscle mechanical function and muscle fiber morphology during short-term immobilization and subsequent retraining. J Appl Physiol 2010;109:(6):1628-34.
20. Hvid LG, Ørtenblad N, Aagaard P, et al. Effects of ageing on single muscle fibre contractile function following short-term immobilisation. J Physiol 2011;589:(19):4745-57.
21. Hvid LG, Suetta C, Nielsen JH, et al. Aging impairs the recovery in mechanical muscle function following 4 days of disuse. Exp Gerontol 2014;52:(1-8.
22. Caserotti P, Aagaard P, Buttrup Larsen J, et al. Explosive heavy-resistance training in old and very old adults: changes in rapid muscle force, strength and power. Scand J Med Sci Sports 2008;18:(6):773-82.
23. Saltin B, Grimby G. Physiological analysis of middle-aged and old former athletes: comparison with still active athletes of the same ages. Circulation 1968; 38:(6):1104-15.
24. Suetta C, Frandsen U, Mackey AL, et al. Ageing is associated with diminished muscle re-growth and myogenic precursor cell expansion early after immobility-induced atrophy in human skeletal muscle. J Physiol 2013;591:(15):3789-804.
25. Baechle TR, Earle RW. Essentials of strength training and conditioning. Hum Kinet, 2008.
26. Jakobsen MD, Sundstrup E, Krustrup P, et al. The effect of recreational soccer training and running on postural balance in untrained men. Eur J Appl Physiol 2011;111:(3):521-30.
27. Guralnik JM, Simonsick EM, Ferrucci L, et al. A short physical performance battery assessing lower extremity function: association with self-reported disability and prediction of mortality and nursing home admission. J Gerontol 1994;49:(2):M85-M94.
28. Sherrington C, Lord SR. Reliability of simple portable tests of physical performance in older people after hip fracture. Clin Rehabil 2005;19:(5):496-504.
29. Bohannon RW. Comfortable and maximum walking speed of adults aged 20-79 years: reference values and determinants. Age Ageing 1997;26:(1):15-9.
30. Suetta C, Magnusson SP, Rosted A, et al. Resistance training in the early postoperative phase reduces hospitalization and leads to muscle hypertrophy in elderly hip surgery patients - a controlled, randomized study. J Am Geriatr Soc 2004;52:(12):2016-22.
31. Alcazar J, Losa-Reyna J, Rodriguez-Lopez C, et al. The sit-to-stand muscle power test: An easy, inexpensive and portable procedure to assess muscle power in older people. Exp Gerontol 2018;112:38-43.
32. McAllister LS, Palombaro KM. Modified 30-second

Sit-to-Stand test: reliability and validity in older adults unable to complete traditional Sit-to-Stand testing. J Geriatr Phys Ther 2020;43:(3):153-8.
33. Jones CJ, Rikli RE. Measuring functional fitness of older adults, J Act Aging, March April 2002, pp. 24–30.
34. Langhammer B, Stanghelle JK. Functional fitness in elderly Norwegians measured with the Senior Fitness Test. Adv Physiother 2011;13:(4):137-44.
35. Aadahl M, Beyer N, Linneberg A, et al. Grip strength and lower limb extension power in 19–72-year-old Danish men and women: the Health2006 study. BMJ Open 2011;1:(2):e000192.
36. Hvid LG, Aagaard P, Ørtenblad N, et al. Plasticity in central neural drive with short-term disuse and recovery-effects on muscle strength and influence of aging. Exp Gerontol 2018;106:145-53.
37. Deschenes MR, Holdren AN, Mccoy RW. Adaptations to short-term muscle unloading in young and aged men. Med Sci Sports Exerc 2008;40:(5):856.
38. Lavin KM, Roberts BM, Fry CS, et al. The importance of resistance exercise training to combat neuromuscular aging. Physiol 2019;34:(2):112-22.
39. Hvid LG, Strotmeyer ES, Skjødt M, et al. Voluntary muscle activation improves with power training and is associated with changes in gait speed in mobility-limited older adults - a randomized controlled trial. Exp Gerontol 2016;80:51-6.
40. Loram ID, Maganaris CN, Lakie M. The passive, human calf muscles in relation to standing: the non-linear decrease from short range to long range stiffness. J Physiol 2007;584:(2):661-75.
41. Fimland MS, Helgerud J, Gruber M, et al. Functional maximal strength training induces neural transfer to single-joint tasks. Eur J Appl Physiol 2009;107:(1):21-9.
42. Fimland MS, Helgerud J, Gruber M, et al. Enhanced neural drive after maximal strength training in multiple sclerosis patients. Eur J Appl Physiol 2010; 110:(2):435-43.
43. de Zwart AH, van der Esch M, Pijnappels MA, et al. Falls associated with muscle strength in patients with knee osteoarthritis and self-reported knee instability. J Rheumatol 2015;42:(7):1218-23.
44. Carneiro MA, Franco C, Silva AL, et al. Resistance exercise intervention on muscular strength and power, and functional capacity in acute hospitalized older adults: a systematic review and meta-analysis of 2498 patients in 7 randomized clinical trials. GeroScience 2021;1-13.
45. Hortobágyi T, Teixeira LA, Duysens J, et al. Is standing sway an accurate measure of fall risk and predictor of future falls in older adults? Braz J Mot Behav 2020;14:(01):1-3.