J. Phys. Ther. Sci. 33: 250–260, 2021

The Journal of Physical Therapy Science

Original Article

The effects of ageing on functional capacity and stretch-shortening cycle muscle power

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Abstract. [Purpose] To examine the effects of age and gender in an ageing population with respect to functional decline and the relationship between muscle power and functional capacity. [Participants and Methods] The cohort (N=154) was subdivided into youngest-old (65–70 years.; n=62), middle-old (71–75 years.; n=46), and oldest-old (76–81 years.; n=46). Measures of mechanical muscle function included countermovement jump height, muscle power, leg strength and grip strength. Functional performance-based measures included heel-rise, postural balance, Timed Up and Go, and gait speed. [Results] The oldest-old performed significantly worse than the middle-old, whereas the youngest-old did not outperform the middle-old to the same extent. Increased contribution of muscle power was observed with increasing age. Males had consistently higher scores in measures of mechanical muscle function, whereas no gender differences were observed for functional capacity. [Conclusion] The age-related decline in functional capacity appears to accelerate when approaching 80 years of age and lower limb muscle power seems to contribute to a greater extent to the preservation of functional balance and gait capacity at that stage. Males outperform females in measures of mechanical muscle function independent of age, while the findings give no support for the existence of gender differences in functional capacity.

Key words: Stretch-shortening cycle muscle power, Physical function, Ageing

(This article was submitted Nov. 9, 2020, and was accepted Dec. 15, 2020)

INTRODUCTION

There has been a substantial increase in life expectancy over the previous century, and the number of very old people aged 80 years and older is growing rapidly. It is possible to postpone morbidity by practicing healthy lifestyles[1)], and health-promoting activities and medical advances have led to an interest in how to promote a healthier old age, i.e. how to age successfully. Further, the increased prevalence of longevity appears to yield fewer, not more, years of disability[2, 3)], although this is a matter of debate[4)].

Lifestyle behaviours such as participating in physical activity can help attenuate the degree of frailty, and the level of physical activity is associated with incidence of frailty[5)]. Loss of muscle strength, walking speed, weight, energy, and physi-

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*Corresponding author. Cecilia Elam (E-mail: cecilia.elam@neuro.gu.se) cal activity are all part of the frailty syndrome[5)]. Hence, it is imperative for the health of older adults to identify those at risk of decline in physical activity levels. Studies show that there is a relationship between frailty and the intensity of physical activity, as opposed to the volume[6, 7)]. In fact, low intensity physical activity such as vacuuming and laundry was not associated with frailty at any age. However, moderate and intense physical activity such as dancing, cycling and brisk walking did show such an association[7)]. Recommendations aimed at reducing physical frailty in older adults are designed to maximize muscle power rather than muscle strength[8, 9)]. Caserotti, Aagaard, Larsen et al.[10)] suggested that heavy-resistance strength training effectively counterbalances the discrepancy between mechanical muscle function and functional demand in the elderly. The age-related loss of muscle mass, sarcopenia, is an undesired pathophysiological component of frailty[11)], and a review summarized that resistance training alone could increase maximal muscle strength by 6.6–37%; muscle mass by 3.4–7.5%; muscle power by 8.2%; and functional capacity and risk of fall by 4.7–58.1%[11)].

A critical determinant of physical function in older adults is muscle power, which is required for everyday tasks such as sit-to-stand movements and gait[12, 13)]. Muscle power is a function of force production and velocity of movement[12, 14)], and the evaluation of the force-velocity relationship in older people can differentiate between participants with varying levels of functional capacity[15)]. The progressive decline in muscle power with aging may compromise mobility and independence, and thus bears important functional consequences[13)]. A decline in lower limb muscle power may also represent an important risk factor for falls[12, 16–20)]. During stretch-shortening cycle (SSC) movements, muscle power can be enhanced by concentric muscle actions preceded by active muscle stretching (eccentric muscle actions), in comparison with concentric muscle actions preceded by a resting or isometric state[15)]. SSC muscle actions are naturally inherent to human movements such as multi-joint weight-bearing activities of daily living (ADL), where coupled eccentric-concentric (i.e. SSC) muscle actions are performed in the lower extremeties during walking, running or stair climbing[12, 21–24)]. Notably, SSC muscle power can also be of vital importance when breaking/reversing a fall[12, 18, 19)].

Previous reports have demonstrated that lower limb muscle power during multi-joint weight-bearing SSC movements, such as the counter-movement jump (CMJ)[12, 13, 25–27)], can be objectively quantified in a reproducible manner in both young and old individuals[28)]. Due to its composite and functional (SSC) nature, CMJ power testing might better reflect typical ADL, such as stair climbing[24)], sit-to-stand and horizontal gait[13)], compared to single-joint concentric-only muscle power tests. Since ageing individuals suffer loss of both strength (force) and velocity[14)], CMJ-based power testing may be indicative of a person's functional capacity[20, 29)], given that skeletal muscle power decreases earlier than muscle strength with advancing age[25, 30, 31)]. However, only limited information exists on weight-bearing coupled eccentric-concentric muscle function in ageing individuals[12)], and its relationship to functional performance has been only minimally examined[32, 33)]. Changes in the *in vivo* force–velocity and power–velocity relationships with increasing age lead to a loss of mobility and independence in older adults[34)]. Compared to muscle strength testing, the assessment of maximal muscle power provides a more predictive tool with regard to frailty, risk of falls, and mortality in older individuals[31)], as well as for the evaluation of functional reserve capacity[35)]. Hence, muscle power appears to represent a sensitive determinant of functional capacity in older persons[34–36)].

It has previously been shown that maximal leg extension power (normalized to body mass) was greater in males than in females throughout the adult life span[28)]. Yet, the age-associated decline was steeper for males, which resulted in a convergence in maximal SSC power production between females and males in old age[28)]. However, Suetta et al.[37)] concluded in a large cohort study (n =1,305) that power-based measures of functional capacity start to decline around the 5th decade, whereas grip strength and gait speed to remain unaltered until the 7th decade. However, it is not clear to what extent the age-associated loss of muscle power relates to a concurrent loss in functional capacity in the various stages of old age.

The present study therefore investigated functional capacity in sub-groups of females and males aged 65–81 years to address the role of muscle power in the expression of functional capacity of individuals approaching very old age compared to the younger old group. Thus, the aims of this study were (i) to compare youngest-old (65–70), middle-old (71–75), and oldest-old (76–81) adults with respect to lower limb mechanical muscle function (strength, power), functional capacity and gender differences, and (ii) to assess the contribution of muscle power and strength to functional capacity in the various stages of ageing.

PARTICIPANTS AND METHODS

This descriptive and explorative study enrolled 154 community-dwelling females (n=81; age: 71.9 ± 4.7 years; height: 1.63 ± 0.05 m; weight: 68.2 ± 10.9 kg) and males (n=73; age: 72.4 ± 4.7 years; height: 1.78 ± 0.07 m; weight: 83.0 ± 11.9 kg) in an age range of 65–81 years (72.1 ± 4.7 years). The inclusion criterion was the ability to perform a vertical countermovement jump to maximal ability. Exclusion criteria were: severe musculoskeletal injuries or problems affecting physical performance; detectable neurological, cardiopulmonary or cognitive problems; or arthroplastic surgery in the lower extremity. Five hundred females and males between 65 and 80 years of age living in the municipality were randomly selected from the national register, and were invited by post to take part in the study. The participants who accepted the invitation were subsequently contacted by a research nurse who conducted the first screening by phone. Of the initial 500, 200 (40%) agreed to participate and 154 (31%) of these met the inclusion criteria (81 females and 73 males). The participants were divided into three groups according to age: youngest-old 65–70 years (females n=33; age: 67.1 ± 1.8 years; height: 1.66 ± 0.1 m; weight: 71.1 ± 12.1 kg; men n=29; age: 67.5 ± 1.7 years; height: 1.78 ± 0.1 m; weight: 84.6 ± 12.2 kg), middle-old 71–75 years (females n=26; age: 72.8 ± 1.4 years; height: 1.62 ± 0.0 m; weight: 64.4 ± 9.2 kg; males n=20; age: 72.9 ± 1.3 years; height: 1.78 ± 0.1 m; weight: 81.3 ± 11.5 kg) and oldest-old 76–81 years (females n=22; age: 78.0 ± 1.6 years; height: 1.62 ± 0.1 m; weight: 68.3 ± 9.8 kg; males n=24; age: 77.9 ± 1.4 years; height: 1.78 ± 0.1 m; weight: 82.4 ± 12.0 kg). All testing was conducted by the same physiotherapist (Author) at an orthopaedic research facility, Lundberg Laboratories at Sahlgrenska University Hospital, University of Gothenburg. All test procedures followed a standardized protocol that was identical for all participants. The Regional Ethical Review Board, Gothenburg, Sweden, approved the study and all study participants gave their written informed consent to the conditions of the study (Dnr: 140-07).

All participants visited the research lab on a single test occasion. Prior to muscle power testing, all participants performed a 5-minute general warm-up on an ergometer cycle at low resistance. Shortly after the warm-up (1–2 minutes), the participants performed various tests after receiving verbal and visual instructions. All participants wore a specific type of athletic shoes (individual size) provided by the research lab.

Body height was expressed in meter (m) and body mass was measured using a digital scale with participants lightly dressed. Dual-energy X-ray absorptiometry (DXA) was used to assess bone, fat, and lean mass, expressed in kilograms or as a percentage of body weight. The DXA measurement was carried out by experienced personnel according to a standardized protocol.

Maximal stretch-shortening cycle leg extension power (SSC P_{peak}) was determined during a standardized stretch-shortening cycle (SSC) movement performed as a maximal bilateral counter-movement jump (CMJ) on a force plate where vertical ground reaction force (Fz) was measured (AMTI OR6-5–1, Watertown, MA 51 × 46 × 8 cm and Kistler 9281 B, Winterthur, Switzerland) as described in detail elsewhere[12, 26, 27, 38)]. With their hands on their hips starting from an upright standing position, all participants were instructed to perform a fast downward movement (eccentric phase) immediately followed by a fast upward movement (concentric phase), and to jump as high as possible[39)]. The jump was visually demonstrated to the participant who subsequently performed 3–5 sub-maximal jumps for practice. If needed (i.e. due to poor balance control), the participant was assisted by the tester (Principal Author) at the instant of landing. The force plate was fitted into a levelled floor to minimize the risk of falls upon landing and to enable the participants to perform to their best ability. After a short rest period, the participant executed three maximal jumps on the force plate separated by a 1-minute rest period between successive trials. Vertical ground reaction force (Fz) was recorded at 1,000 Hz using an external A/D converter as described in detail elsewhere[12)]. The jump with the highest height was selected for further analysis, including identification of peak power during the take-off (SSC P_{peak}), as previously described[12, 27, 28)]. In brief, vertical velocity (V) of the body centre of mass (BCM) was found by time integration of the instantaneous acceleration signal ($\int([Fz/m]-g)\,dt$), where m=body mass, and gravitational acceleration ($g=9.81\ m/s^2$). Subsequently, the vertical position of the BCM was obtained by time integration of the velocity signal ($\int V\,dt$). Throughout the entire movement, instantaneous power (Watt) exerted on the BCM was calculated as the product of vertical ground reaction force (F) and BCM velocity (V) during the concentric take-off phase (positive V). Peak power (P_{peak}) was identified as the maximal (peak instantaneous) power produced in this phase. Maximal vertical jump height (JH) was derived from the vertical BCM velocity at the instant of take-off ($JH=V_{takeoff}{}^2/2\ g$)[12, 28)]. The CMJ power test has previously been validated in various study populations covering a wide age range[33)], as well as in elderly individuals separately[27)].

Maximal voluntary isometric contraction strength (MVC) was measured for the quadriceps muscle using a strain gauge apparatus (Steve Strong®, Stig Starke HB, Goteborg, Sweden) attached via a stiff nylon strap to a cuff firmly fastened to the ankle. The participant was placed in a supine position with 90° hip flexion. The strap length was individually adjusted to each participant to ensure a knee joint angle of 90°. The cuff's lower edge was placed over the proximal part of the lateral malleolus and the strap with the strain gauge was adjusted to run horizontally to the floor and could be adjusted vertically to fit participants with varying lower limb lengths. A small back rest supported the participant and their thighs were strapped down to the seat using a Velcro belt. The participants were asked to keep their arms crossed over their chest while performing a maximal contraction of the quadriceps muscle for a 5-second duration. Three trials were performed for each side separated by 45-second rest periods. While no verbal encouragement was given during data sampling, prior to each trial the participants were encouraged to perform to their maximal ability. The highest force value (i.e. peak force) for each leg was stored for further analysis. The Steve Strong has been subjected to test-retest assessment in healthy men and patients with chronic obstructive pulmonary patients and is shown to have high reliability (unpublished data)[40)].

Isometric grip strength (Grip) was measured with an electronic cylindrical grip device (Grippit, AB Detector)[41)]. The grip device and arm support were mounted on a portable base and rested on a height-adjustable table. The participant sat in a height-adjustable chair without an armrest as close as possible to a 90° hip flexion with both feet firmly placed on the floor. The elbows were flexed at a 90° angle with the hands and shoulders in neutral positions. Three trials were performed for each hand (always starting with the right hand) interspaced by 45-second pause periods. No verbal encouragement was given during data sampling, however prior to each trial participants were encouraged to perform to their maximal ability. The recordings involved a 10-second maximum voluntary contraction (MVC), using the highest MVC value (peak force) of each hand for analysis.

Lower leg muscle endurance was assessed using the unilateral heel rise test (HRT)[42)]. The test was performed with the participant standing on one foot on a 10° tilted wedge using standardized footwear (described above). Postural balance was supported by lightly touching the wall with the fingertips and hands held at shoulder level. During the test, a metronome marked the cadence of the movement (60 bpm) that corresponded to a mean ankle angular velocity of approximately 60°/s, while the knee was kept straight. After a couple of trials with the left foot to allow the participants to familiarize themselves with the procedure, the HRT always started with the right foot. The participant was instructed to lift the heel as high as possible at the pre-set frequency until no further heel-rises could be performed (cadence failed to be sustained). Subsequently, the procedure was repeated with the left foot. One trial per foot was conducted and the number of heel rises was counted and registered.

Postural balance (PB) was evaluated with a single-leg stance test—the amount of time that the participant could stand on their self-selected best foot without hand support with their eyes open[43)]. Participants were instructed to stand on the preferred leg within a circle of 50 cm Ø, with eyes open and no hand support. The contralateral foot was not allowed to touch the floor (toes positioned at the level of the medial malleolus of the standing leg). No contact between legs was allowed. Arms were free to move for balance. Time to loss of balance (defined as touching the ground with their contralateral foot) was measured in seconds with a digital stopwatch. The maximum score was 30 seconds, after which time the test was stopped.

Dynamic mobility balance and agility were assessed using the Timed Up and Go Test (TUG)[44)]. A distance of 3 metres was marked on the floor. The starting position of the participants was seated in an armchair, back against the back rest and arms resting on the arms of the chair, which was of a standard height. The participants received instructions to walk the marked 3-metre distance at their normal speed, then cross the line before turning around and walking back to sit down in the chair again. The timing of the TUG started when the participant's back rose from the chair. The participants performed three trials, and the fastest trial measured in seconds was registered.

Habitual and maximal horizontal gait speed were assessed with the 30-metre walk test (30mWT)[45)]. The test was performed in a quiet straight corridor from a standing start with the participant positioned behind a starting line marked on the floor with tape. The timer was started once the participant initiated walking and their first foot passed the starting line. The timer was stopped when the participant's first foot passed the line on the floor marking the 30-metre distance. Each participant performed this walk twice. The first trial was conducted at the participant's self-selected speed (30mWT-self). Before the second trial, the participant was instructed to walk as fast as possible without running, to assess maximal walking speed (30mWT-max). The examiner walked behind the participant for all tests. The time for each trial was recorded in seconds with a stopwatch, and mean 30-metre gait speed was calculated and expressed in metres per second (m/s).

Group means and standard deviations (SD) were calculated to describe all continuous variables. Data were checked for outliers and for normality with histograms and tests of skewness and kurtosis for normality. The results showed that all data were normally distributed for both genders. Given that gender has a fundamental role in stretch-shortening cycle muscle power[12, 28)], some of the analyses were split by gender. Differences between females and males within their respective age groups were evaluated using an unpaired Student's t-test. Comparisons between age groups (each group vs. the precedent) with respect to stretch-shortening cycle peak muscle power and outcome parameters for mechanical muscle function and functional capacity were analysed by two-way analyses of variance (ANOVA). When significant differences were detected, post hoc analyses with Tukey's test were made to compare the different age groups (65–70 years, 71–75 years and 76–81 years). Univariate linear regression analyses were performed (Pearson's product-moment method) to assess the unique contribution of age to stretch-shortening cycle peak muscle power, isometric lower limb muscle strength, and functional capacity. Univariate linear regression analysis was also performed to evaluate the relationship between $SSC\ P_{peak}$ and other measures of mechanical muscle function as well as functional capacity. The assumption of linear function effects was examined by plotting outcome parameters vs explanatory variables. Descriptively, beta-coefficients with 95% confidence intervals (CIs) were derived using linear regression analysis to quantify the change in outcome variable by a 1-unit increase in the explanatory variable, along with the associated p-value and r^2 (coefficient of determination, or the explained amount of variance). Analyses were performed with the Statistical Package for the Social Sciences SPSS v.24.0 (IBM Corp., Armonk, NY, USA). All statistical tests were two-tailed and $p<0.05$ was considered statistically significant.

RESULTS

Mean age and anthropometric characteristics of the male and female participants are presented in Table 1, with no differences observed between groups. Table 2 shows mean scores for SSC P_{peak} and all measures of functional capacity, stratified by age group and gender. SSC P_{peak} was higher in males than in females in all three age groups ($p\leq0.01$, $p=0.001$ and $p=0.01$, respectively) which was noted for JH as well ($p<0.001$; $p<0.01$; $p<0.05$) (Table 2). Likewise, maximal muscle strength (MVC, Grip) was higher in males compared to females in all age groups (Table 2). In contrast, females performed similarly to males across all age groups in HRT, PB, TUG and 30mWT, while males in the youngest-old age group outperformed females in 30mWT-max testing ($p<0.001$).

There was an overall trend towards an age-related decline in functional capacity for both males and females (Table 2). The univariate linear regression analysis showed that age accounted for 10–15% of the variance in SSC P_{peak}, PB, TUG and 30mWT, and below 10% of the variance in JH, MVC, Grip and HRT (Table 2). The results of the comparisons between age groups by means of ANOVA showed that out of all measures obtained, middle-old individuals performed significantly poorer on two measures compared to youngest-old: left-handed grip strength for females and maximum gait speed for males (indicated by ¥, Table 2). In contrast, oldest-old males demonstrated lower ($p<0.01$–0.05) outcome measures compared to

Table 1. Age and anthropometric characteristics by gender and age groups

		65–70 years Male (n=29) Female (n=33)	Gender difference	71–75 years Male (n=20) Female (n=26)	Gender difference	76–81 years Male (n=24) Female (n=22)	Gender difference
Outcome	Gender	Mean (SD)	p-value	Mean (SD)	p-value	Mean (SD)	p-value
Age (years)	M	67.48 (1.68)	0.35	72.85 (1.31)	0.92	77.88 (1.36)	0.86
	F	67.06 (1.80)		72.81 (1.36)		77.95 (1.59)	
Height (m)	M	1.78 (0.08)	<0.001	1.78 (0.07)	<0.001	1.78 (0.06)	<0.001
	F	1.66 (0.05)		1.62 (0.04)		1.62 (0.05)	
Weight (kg)	M	84.57 (12.20)	<0.001	81.25 (11.52)	<0.001	82.38 (11.98)	<0.001
	F	71.07 (12.07)		64.41 (9.22)		68.32 (9.84)	
BMI (kg/m^2)	M	26.74 (3.17)	0.34	25.67 (2.40)	0.24	26.08 (3.18)	0.94
	F	25.83 (4.10)		24.65 (3.21)		26.16 (3.88)	
Bone mineral (kg)	M	3.27 (0.53)	<0.001	3.24 (0.53)	<0.001	3.12 (0.47)	<0.001
	F	2.39 (0.36)		2.11 (0.41)		2.23 (0.40)	
Fatfree tissue (%)	M	56.83 (6.44)	<0.001	54.38 (5.59)	0.001	54.47 (6.62)	<0.001
	F	39.93 (3.54)		38.30 (3.58)		38.49 (3.08)	
Fat (%)	M	28.49 (7.33)	<0.001	28.86 (6.45)	0.001	29.96 (5.50)	<0.001
	F	39.09 (7.67)		36.24 (7.19)		39.55 (5.92)	

BMI: Body mass index. P-values show difference between males and females.

youngest- and middle-old males for a majority (11 out of 12) of the obtained measures; SSC P_{peak}, JH, right- and left-sided MVC, Grip, HRT, PB, TUG, and 30mWT (Table 2). Likewise, oldest-old females showed lower ($p<0.05$) outcome measures compared to that of youngest- and middle-old females for the majority of 12 measures obtained: SSP P_{peak}, JH, Grip, HRT, TUG and the two different gait speeds 30mWT-self/max (Table 2). In males, SSC P_{peak} was 5.9% lower in the middle-old compared to the youngest-old (27.3 vs 29.0 W/kg). In turn, oldest-old males demonstrated 13.7% lower SSC P_{peak} compared to the middle-old (27.3 vs. 23.5 W/kg; $p<0.05$) (Table 2). Similar trends were observed in females, with the oldest-old demonstrating 16% lower SSC P_{peak} compared to the middle-old (18.9 vs 22.5 W/kg; $p=0.004$), whereas no difference in SSC P_{peak} was observed between middle-old and youngest-old ($p=0.47$) females.

Results of the linear regression analysis are shown in Table 3. The age-related variance in SSC P_{peak} explained 66–69% of the variance in maximal vertical JH ($p<0.001$). In the youngest-old, SCC P_{peak} explained 24 and 26% of the variance in right- and left-sided maximal leg extension strength, respectively (Table 3). The corresponding coefficients of determination (explained variance) for the middle-old and oldest-old were somewhat higher compared to the youngest-old as seen in Table 3 (37/40% and 33/40%, respectively). Further, SSC P_{peak} explained 27–38% of the age-related variation in grip strength, with similar R^2 values in the various age groups. SSC P_{peak} also explained the variance in HRT, PB and TUG although to a lesser degree (Table 3). However, in youngest-old and middle-old participants, SSC P_{peak} did not significantly contribute to the variation in self-selected gait speed, while in contrast SSC P_{peak} explained 41–54% of the variance in self-selected and maximum gait speed for the oldest-old (Fig. 1), while contributing much less (16–19%) in the youngest-old and middle-old participants.

DISCUSSION

The present study data indicate that there is a threshold, a sort of critical age of 75+ years where peak muscle power starts to contribute to a greater extent in everyday ambulatory tasks, suggesting that the oldest-old are approaching their maximal functional capacity in a number of everyday activities, independent of gender. Moreover, increasing age per se seems to contribute to a greater extent to the decline of SSC P_{peak} (W/kg), balance (sec) and gait speed (m/s), compared to isolated muscle strength (N). This is in line with previous studies where a reduction in contractile force production and contraction speeds with increasing age results in an overall slowing of specific movement tasks[46–49)]. Furthermore, in the present study a linear decline in SSC muscle power and muscle strength in absolute values was observed with increasing age, especially in males. Albeit not significantly so, the oldest-old participants performed significantly poorer than the middle-old, while the youngest-old participants did not outperform the middle-old to the same extent. These observations support the notion that the oldest-old category (>75 years) represents a distinct stage of life[50, 51)]. In the present study, SSC P_{peak} declined up to 100% faster between oldest-old and middle-old males compared to the reduction observed between middle-old and youngest-old males (14.7% vs. 5.9%). A similar trend was noted for females, where the corresponding declines amounted to 16% and 5%, respectively. Thus, in contrast to previous reports comparing young and old adults[28)], SSC P_{peak} did not decline at a constant

Table 2. SSC muscle power, vertical countermovement jump height, isolated muscle strength and functional capacity split by age group and gender

		65–70 years Male n=29 Female n=33	Gender difference	71–75 years Male n=20 Female n=26	Gender difference	76–81 years Male n=24 Female n=22	Gender difference	ANOVA	Univariate linear regression with age as independent variable		
Outcome	Gender	Mean (95% CI)	p-value	Mean (95% CI)	p-value	Mean (95% CI)	p-value	p	R^2	Beta (95% CI)	p
SSC P_{peak} (W/kg)	M	28.95 (4.41)	***	27.25 (5.47)	***	23.52 (5.14)†‡	**	***	0.10	−0.33 (−0.54;−0.21)	***
	F	23.65 (3.81)		22.53 (3.35)		18.92 (4.09)†‡		***			
JH (cm)	M	24.84 (5.46)	***	22.76 (4.78)	**	19.60 (6.00)†	*	**	0.07	−0.27 (−0.51;−0.14)	***
	F	19.15 (4.30)		18.54 (3.55)		16.09 (5.69)†		*			
MVC (R) (N)	M	460.38 (119.65)	***	414.20 (85.68)	***	355.54 (91.40)†	***	**	0.05	−0.23 (−9.54;−1.77)	**
	F	302.24 (88.70)		257.88 (81.92)		263.27 (69.75)					
MVC (L) (N)	M	466.69 (115.28)	***	438.05 (73.94)	***	331.33 (90.54)†	**	***	0.07	−0.26 (−10.63;−2.77)	***
	F	296.42 (81.93)		247.38 (81.88)		264.00 (68.79)					
Grip (R) (N)	M	417.55 (87.76)	***	431.30 (57.95)	***	368.33 (95.12)‡	***	*	0.01	−0.11 (−6.57:1.26)	
	F	243.15 (57.60)		227.88 (53.84)		196.73 (49.33)†		*			
Grip (L) (N)	M	417.69 (74.12)	***	399.65 (55.89)	***	355.58 (94.29)†	***	*	0.03	−0.17 (−7.92;−0.38)	*
	F	244.82 (47.88)		209.85 (48.60)¥		176.82 (49.36)†		***			
HRT (R) (number)	M	12.93 (8.16)		11.45 (8.03)		7.75 (7.36)			0.08	−0.29 (−0.74;−0.23)	***
	F	12.06 (9.20)		8.15 (6.21)		5.77 (5.06)†		**			
HRT (L) (number)	M	12.76 (10.48)		8.55 (7.97)		6.00 (5.99)†		*	0.07	−3.52 (−0.73;−0.20)	***
	F	10.7 (8.68)		7.42 (6.18)		6.45 (6.25)					
PB (sec)	M	27.10 (5.51)		25.30 (8.78)		20.21 (11.29)†		*	0.14	−0.38 (−1.03;−0.47)	***
	F	28.24 (4.40)		23.08 (9.64)		17.86 (11.31)†		***			
TUG (sec)	M	7.38 (0.98)		7.65 (1.04)		8.83 (1.76)†		***	0.11	0.33 (0.06;0.16)	***
	F	7.39 (1.52)		7.77 (1.27)		8.86 (2.21)†		**			
30 m Self (m/s)	M	1.47 (0.15)		1.43 (0.13)		1.29 (0.20)†		***	0.13	−0.37 (−0.02;−0.01)	***
	F	1.47 (0.22)		1.38 (0.18)		1.28 (0.24)†		**			
30 m Max (m/s)	M	2.31 (0.39)	***	2.06 (0.22) ¥		1.87 (0.37)†		**	0.15	−0.40 (−0.04;−0.02)	***
	F	1.99 (0.27)		1.97 (0.29)		1.71 (0.30)†‡		***			

M: Men; W: Women; SSC P_{Peak}: Stretch-shortening cycle peak muscle power; JH: Jump height; MVC: Maximum voluntary contraction; Grip: Grip strength (Grippit); HRT: Heel rise test; PB: Postural balance, time for sustained standing on one leg with eyes open; TUG: Timed-Up and Go; 30mWT: 30-meter walk test; Self: Self-selected speed; Max: Maximum speed. Data is total mean value and standard deviation (SD) split by age group and gender. P-values show difference between men and women: p<0.05*, 0.01**, 0.001***. Statistically significant differences between age groups in men and woman: †: Age 65–70 vs. Age 76–81; ¥: Age 71–75 vs. 65–70; ‡: Age 76–81 vs. Age 71–75.

rate in the present investigation, but rather demonstrated an accelerated decline rate when approaching the 8th decade, as recently also reported in a large-scale population (n=1,305) using concentric-only muscle power testing[37].

The impact of ageing on gait speed depends on the function and interplay of the musculoskeletal, visual, central nervous, and peripheral nervous system, as well as cardiorespiratory fitness and energy production and delivery[52, 53]. Gait speed is a frequently used measure in the clinic to evaluate changes in health and physical function[54]. In the present study both maximum and self-selected gait speed (30mWT-self/max) were lower in the oldest-old males and females compared to the younger age groups. Notably, in the oldest-old (but not the younger) group, SSC P_{peak} was a strong contributor to horizontal gait speed, in particular 30mWT-max (R^2=0.54). Such associations between peak lower limb muscle power and maximum gait speed (present study), skeletal muscle mass[37] and health[54] are consistent with the notion that reduced gait speed represents a functional sign of advancing age[55]. In contrast, Siglinsky et al.[32] reported gait speed to have the weakest relationship with age (R^2=0.04 vs. 0.13/0.15), which is somewhat surprising given that previous studies have demonstrated that gait speed may predict overall health, falls, fractures, and death in older adults[56–58].

The present data demonstrate consistent gender differences in mechanical muscle function (SSC P_{peak}, JH, MVC, Grip) across the ageing lifespan, whereas no gender differences were observed for various functional performance-based measures (postural balance, TUG, 30mW). These observations are in line with previous reports, demonstrating significant gender differences for specific muscle function tests (grip strength and muscle power), but not for physical function tests such as maximal gait speed[32]. Explaining at least in part the consistent gender differences in mechanical muscle function, males are characterized by greater absolute and relative lean muscle mass than females when compared at any given age[32, 37, 59, 60]. These findings, together with the accelerated age-related decline in functional capacity after the age of 75, emphasize the challenges associated with choosing outcome measures of high common clinical relevance and sensitivity in a broader

Table 3. Linear regression models for the association (correlation) between SSC peak muscle power versus vertical countermovement jump height, isolated muscle strength and functional capacity, respectively, split by age groups

	65–70 years n=62			71–75 years n=46			76–81 years n=46		
Outcome parameter	Beta (95% CI)	R^2	p-value	Beta (95% CI)	R^2	p-value	Beta (95% CI)	R^2	p-value
JH (cm)	1.0 (0.8; 1.1)	0.69	***	0.8 (0.6; 0.9)	0.66	***	1.0 (0.8; 1.2)	0.66	***
MVC (R) (N)	13.2 (7.2; 19.3)	0.24	***	14.1 (8.5; 19.6)	0.37	***	10.3 (5.8; 14.8)	0.33	***
MVC (L) (N)	13.8 (7.8; 19.7)	0.26	***	15.8 (10.0; 21.6)	0.40	***	10.7 (6.7; 14.6)	0.40	***
Grip (R) (N)	14.1 (9.3; 19.0)	0.36	***	12.2 (6.1; 18.3)	0.27	***	12.5 (6.9; 18.1)	0.32	***
Grip (L) (N)	13.0 (8.5; 17.6)	0.36	***	13.5 (8.2; 18.7)	0.38	***	13.7 (8.2; 19.2)	0.36	***
HRT (R)	0.6 (0.2; 1.1)	0.12	**	0.7 (0.3; 1.1)	0.25	***	0.6 (0.3; 0.9)	0.24	**
HRT (L)	0.8 (0.0; 1.2)	0.14	**	0.6 (0.2; 1.0)	0.19	**	0.6 (0.3; 0.9)	0.26	***
PB (sec)	0.6 (0.2; 1.1)	0.12	**	0.7 (0.3; 1.1)	0.25	***	0.6 (0.3; 0.9)	0.24	**
TUG (sec)	−0.0 (−0.1; 0.0)	0.06		−0.1 (−0.1; 0.0)	0.05		−0.1 (−0.2; −0.1)	0.18	**
30mWT Self (m/s)	0.0 (−0.0; 0.0)	0.02		0.0 (−0.0; 0.0)	0.06		0.0 (0.0; 0.0)	0.41	***
30mWT Max (m/s)	0.0 (0.0; 0.1)	0.19	***	0.0 (0.0; 0.0)	0.16	**	0.1 (0.0; 0.0)	0.54	***

JH: Jump height; MVC: Maximum voluntary contraction; N: Newton; R: Right; L: Left; Grip: Grip strength; HRT: Heel rise test; PB: Postural balance, time for sustained standing on one leg with eyes open; TUG: Timed-Up and Go; 30mWT: 30-meter walk test; Self: Self-selected speed; Max: Maximum speed. P-values show significance between SSC P_{peak} and outcome measures p<0.05*, 0.01**, 0.001***.

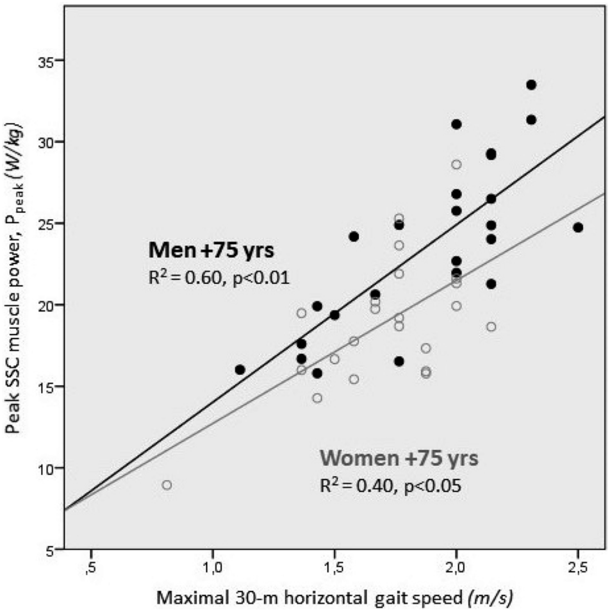

Fig. 1. Correlation between lower limb SSC peak muscle power (SSC P_{peak}) and 30-m maximal horizontal gait speed assessed (30WT-max) in females (n=22) and males (n=24) aged ≥75 years.

age and gender spectrum of older adults[61] in order to detect a deteriorating level of physical activity and hence functional capacity.

One of the inherent features of human ageing is the progressive decline in skeletal muscle mass and maximal muscle force, respectively. Although maybe not as marked as previously thought[37], the age-related loss in skeletal muscle mass can in severe instances reach a loss of up to 50% by the 8–9th decade of life[62]. The markedly lower functional capacity demonstrated in the present group of oldest-old indviduals thus at least in part likely stems from an accelerated decline in muscle mass and resulting impairments in mechanical muscle function (force, power) when approaching very old age.

Level of physical activity as well as intrinsic factors can modify age-related loss in muscle size and function[37]. Considered one of the most important components in frailty prevention, physical activity[63] and resistance training per se is an important strategy to improve muscle mass, muscle strength, and muscle power[11]. However, muscle power, being the product of contractile force and movement velocity, is a stronger predictor of frailty than muscle strength[18, 19]. Therefore, as a countermeasure, physical activity with the specific aim of reducing physical dependency in ageing individuals should be designed to maximize muscle power[8–10].

Although considered the gold standard method for the quantification of SSC lower limb muscle power, the force plate method is both expensive and time consuming and therefore primarily suited for research. However, it remains imperative to identify pre-frail individuals who are on the threshold of not managing everyday activities, so it is important to determine alternative outcome measures that relate to peak muscle power. The present data demonstrate that maximal vertical JH has a very strong correlation with SSC P_{peak}, independent of gender and age, and there seems to be a gradual increase in the strength of this association around the 8th decade. Possibly because of this specific relationship, JH has been reported as superior to traditional outcome measures in distinguishing between sarcopenic and non-sarcopenic old adults while in part also attributable to its strong correlation with lean mass (DXA) and various tests on functional capacity[32]. It is possible that the assessment of JH as a proxy measure of lower limb muscle power should be used in combination with the recording of 30mWT-max to provide a stronger predictive tool of pre-frailty in old adults (+75 years).

The present study examined older people who maintained an independent lifestyle, but who were not free from pathologies, thus representing a realistic sample typically seen by general practitioners and physiotherapists in the clinical setting. More specifically, study participants were community-dwelling individuals and fairly active people despite being affected by a number of pathologies. In a more general context, ageing can be considered a complex multifactorial process in which the decline in mobility is caused by a combination of factors, one being the irreversible process of ageing[64], the second being primary diseases or injuries[65], and the third being deconditioning caused by a sedentary lifestyle[66]. Healthy aging is also typically accompanied by a decline in the contractile efficiency of skeletal muscle[49, 67], which incorporates both quantitative and qualitative muscular changes[68, 69]. A recent review[62] suggests that the two underpinning mechanisms regulating declines in muscle mass and function are muscle fibre atrophy and muscle fibre loss (hypoplasia). Vandervoort[69] and Andersen[70] concluded that there is a selective loss in fast-twitch type II myofibre area, compared to a less marked loss in slow-twitch type I fibre area with ageing, and consequently, contractile power production declines at a steeper rate compared to that of maximal muscle strength with increasing age[31, 71]. This notion is supported by the present study, where more pronounced age-related differences were observed between age groups with respect to SSC P_{peak} for leg extensor strength. In addition, impairments in voluntary neuromuscular activation caused by age-related changes in nervous system function[49, 72] may further reduce the capacity to rapidly develop high muscle power in situations where fast muscle actions are vital (e.g. in abrupt perturbations of postural balance)[49, 73].

Delaying or attenuating the deleterious effect that age has on maximal muscle strength and muscle power with physical activity and pre-habilitative training would be expected to result in improved quality of life in the ageing population[74]. However, the choice of inexpensive yet valid and sensitive outcome measures poses a challenge for health care professionals working in this field. A better understanding of what these instruments are actually measuring and how they relate to maximal muscle power as examined in the present and previous investigations[37, 75] is an important prerequisite for designing test paradigms that can more sensitively identify pre-frail persons at elevated risk for loss of independence. The present data suggest that the age-related decline in functional capacity does not accelerate in humans before they approach very old age (75 years). In support of this notion, Suetta[37] in a recent large cohort study concluded functional parameters such as grip strength and gait speed remain unaltered until the age +70 years[37].

Although we believe that the present study population is representative for community-dwelling ageing individuals and the data comprise a broad range of functional measures, a number of methodological aspects may deserve mentioning. The present study protocol included a range of well-established measures of functional capacity and maximal muscle strength commonly used in the clinical setting. However, the present plantar flexor fatigue test was highly challenging for the oldest individuals. The test is demanding since it requires not only plantar flexor muscle strength, but also a certain degree of postural stability and an ability to follow the pace for the test movement. In hindsight, this fatigue protocol may have been too demanding for some participants, causing test failure to occur due to a lack of postural stability and pace control, not muscle fatigue. Conversely, assessing postural balance by standing on one leg with eyes open may not have been sufficiently challenging for the two younger age groups, where a majority of the participants was found to reach a celing effect (test terminated when exceeding 30 seconds of single leg standing).

In conclusion, when approaching the 8th decade, the age-related decline in functional capacity appears to accelerate, while at the same time maximal lower limb SSC muscle power seems to more strongly contribute to balance and gait capacity. This suggests that the implementation of exercise protocols to improve maximal muscle power becomes of increasing importance in adults approaching very old age (+75 years). The present results also stress the need for effective clinical diagnostic tools to evaluate loss of skeletal muscle mass, impairments in muscle strength, and reductions in functional capacity in the clinical setting in order to facilitate early intervention activities with the aim of attenuating the loss of functional capacity and enabling individuals to sustain or even improve quality of life at the later stages of their lives.

ACKNOWLEDGEMENTS

We would like to thank the Lundberg Laboratories for Orthopaedic Research, Sahlgrenska University Hospital, Gothenburg, Sweden for valuable assistance during the study. This study was supported by the Solstickan Foundation, the Local Research and Development Board for Gothenburg and Södra Bohuslän, the Doctor Felix Neuberghs Foundation, the Renée Eanders Foundation, and the Foundation for Rehabilitation and Medical Science.

Conflict of interest

None.

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