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Original Article

Cross-sectional assessment of neuromuscular function using mechanography in women and men aged 20-85 years

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Abstract

Objectives: The aim of this cross-sectional study was to examine the influence of age and sex on neuromuscular function of the lower limbs using mechanography. 704 adults aged 20-85 years from Germany participated in this study. **Methods:** Ground reaction force and power were assessed with countermovement jumps and the chair rising test on a ground reactions force plate. **Results:** While ground reaction force per unit body mass declined by about 20% from the third to the ninth decade, the decline of power per unit body mass was much greater, varying between 40-50%. Men and women are affected equally by the decline. Age and sex explained the variability of the power parameters to a much greater extent (R^2=0.54 to R^2=0.70) than the force parameters (R^2=0.18 to R^2=0.36). **Conclusions:** Our reference values can help to identify those who might be affected by the development of sarcopenia. Preventive exercise programs should focus on preserving muscle power in addition to the training of muscle force.

Keywords: Jumping Performance, Sit-to-stand Performance, Ageing, Sex Differences, Reference Values

Introduction

It is well established that the aging process is accompanied by the gradual loss of muscle function. Age associated changes in muscle function are characterized by a decrease in lean body mass[1-3] and in muscle strength. A major problem in the literature is the ambiguous use of the term "muscle strength" as it is used for different qualities of muscle function, such as isometric force, isokinetic torque or power. Age related decline has been reported for isometric force[4-10] and for torque[5,6,8,11,12]. The loss of muscle mass as well as the loss of muscle force respectively torque are strongly linked to physical impairment and disability in the elderly[5,13-18]. Some studies indicate that the loss of isometric force[7] and torque[11] is even higher than the decline in muscle mass[7,11].

An increasing number of studies on muscle and aging emphasize the role of muscle power as its relationship to functional status is more significant than muscle force[19,20], muscle torque[21,22] or muscle mass[23]. Cross-sectional studies have illustrated the muscle power decline in men[24,25] as well as in both genders[5,26]. Two cross-sectional studies in which muscle force/torque and muscle power have been described in a large representative sample, indicate that muscle power declines to a larger extent than isometric force[7] and torque[5].

Though force plate technology is widely used in clinical and research settings, a review of the literature reveals a deficiency of norm values on ground reaction force plate measurement as it relates to age and sex in a large population-based study. In the present study we used mechanography for motion analysis with the Leonardo force platform system (Novotec Medical, Pforzheim, Germany). The system records the time course of ground reaction forces, velocity of the vertical movements of the centre of gravity and power as the product of force and velocity. This mechanical approach allows the assessment of complex physiological movements such as jumping or sit-to-stand movement which can be utilized as an indicator for global neuromuscular function[27-30]. Instead of employing additional weights, the individual body weight against gravity is analysed, which makes the testing procedures comparable to everyday conditions. The primary aim of this population based cross-sectional study is to examine the influence of age and sex on neuromuscular function using mechanography. An ad-

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ditional objective of our study is to determine reference data across the life span for jumping performance as well as the sit-to-stand performance for this device.

Methods

Study sample

For this population-based cross-sectional study participants were recruited from a random sample of all districts in Berlin/Germany provided by the resident registration office. Sample size was calculated to be 30 women and 30 men in each 5-years band between 20 and 85 years stratified for sex. The entry criteria for the study excluded those with (a) invalid estimates of body composition due to the presence of metal implants or artificial prostheses, oedema or medications affecting water-mineral homeostasis, (b) inability to walk without walking aid, (c) pregnancy, (d) no allowance for X-ray exposure or (e) inability to understand the nature of the study and to follow the instructions.

Measures

Anthropometry. Body weight was determined to the nearest 0.1 kg, and stature was assessed to the nearest 0.1 cm using a digital weight scale and stadiometer (Seca 764). All participants were measured between 9 and 11 am in underwear without shoes. Body mass index (BMI) was calculated as weight (kg) divided by height (m^2).

Assessment of physical performance. To assess ground reaction force and peak mechanical power of the lower extremity we used the Leonardo Mechanograph® Ground Reaction Force Plate (Novotec Medical, Pforzheim, Germany; software package 4.2). The platform is composed of two symmetrical force plates measuring the vertical ground reaction force exerted onto the platform. Before every test, the device determines subjects' body weight for use in subsequent calculations. The examiner demonstrated all testing procedures to the participants prior to the measurement.

Three two-leg jumps (2LJ) were performed as a countermovement jump (brief squat before the jump with freely moving arms) with a break of 1 min between each jump. Participants were instructed to jump as high as possible and verbal encouragement was given for every jump. For analysis, the maximal total relative force per body weight during lift off in N/kg (2LJF), maximal total relative power per body weight during lift off in W/kg (2LJP) and the maximal vertical velocity during lift off in m/s (2LJvV) were used and the best of the three tests was taken.

In analogy to the chair rise test commonly used in geriatric assessment[31] the chair-rise test (CRT) was performed on a bench of 45 cm height without arm rests, which is anchored onto the force plate (Figure 1). The participants were instructed to fold their arms in front of their chest. The time was measured for the duration each participant needed to stand up and sit down five times at maximum speed without using the arms under continual verbal encouragement. This test was performed only once. For analysis, the maximal total relative force per body weight during the rise phases of five chair stands in N/kg (CRTF), total relative power per body weight during the rise phases of five chair stands in W/kg (CRTP) and the vertical velocity during lift off in m/s (CRTvV) were used.

Figure 1. Chair rise test on the Leonardo platform.

Sufficient reproducibility for both tests has been documented in children, young adults as well as in physically competent older individuals[32,33]. To ensure consistency the same examiner performed all testing procedures.

Statistical analysis

Descriptive statistics for anthropometric data and neuromuscular performance parameters are presented as means±standard deviations. Additionally, neuromuscular performance performance parameters are presented in median and as a percentage compared to the mean of the youngest age-decade. One-way ANOVA was performed to evaluate differences between age-decades in the performance tests. Significant differences were determined with Dunnetts' tests using the young adults (20-29 years) as a reference group.

We performed linear regression analysis to investigate age and sex-related differences in the performance tests. Exploratory graphical analysis was conducted using residual plots and scatter plots with LOESS curves. A quadratic term for age was entered into the models to account for possible curve-linear associations. Sex-specific differences for slope were eval-

	Women (n=351)						
	Age decade						
	20-29	**30-39**	**40-49**	**50-59**	**60-69**	**70-79**	**80+**
n	43	55	56	62	62	50	23
Age (yrs)*	24.9±2.2	34.3±2.8	44.9±2.7	54.8±2.9	64.0±2.6	74.2±3.4	81.8±1.7
Weight (kg)	63.7±11.0	68.2±11.6	69.9±11.5	68.9±12.9	68.2±10.3	69.6±10.2	64.0±6.0
Height (cm)	168.7±6.2	167.8±7.6	166.5±6.5	164.3±4.7	161.6±4.9	160.2±6.6	159.4±6.5
BMI (kg/m²)	22.3±3.1	24.3±4.3	25.3±4.5	25.5±4.4	26.1±3.7	27.2±4.1	25.3±3.2
	Men (n=353)						
	Age decade						
	20-29	**30-39**	**40-49**	**50-59**	**60-69**	**70-79**	**80+**
n	46	58	49	58	57	56	29
Age (yrs)	25.2±2.2	33.9±2.3	45.1±2.9	54.5±3.0	64.7±2.6	75.0±3.5	82.6±1.7
Weight (kg)	78.8±13.2	81.7±11.9	84.1±13.8	83.8±10.8	84.0±13.0	81.8±11.7	78.5±11.8
Height (cm)	180.3±7.0	178.7±6.4	179.0±7.6	178.3±6.7	173.2±6.1	171.1±6.5	173.3±6.1
BMI (kg/m²)	24.2±3.4	25.6±3.4	26.2±3.5	26.4±3.2	28.0±3.9	27.9±3.3	26.1±3.4
** Data are presented in mean±SD*							

Table 1. Study characteristics by sex and age decade.

	Women (n=351)						
	Age decade						
	20-29	**30-39**	**40-49**	**50-59**	**60-69**	**70-79**	**80+**
2LJF (N/kg), mean±SD (%)[†]	24.6±3.2 (100)	24.3±3.6 (99)	23.3±3.2 (95)	23.0±3.7 (93)*	22.1±2.7 (90)*	21.5±2.0 (87)*	19.9±2.4 (81)*
Median	24.4	23.3	22.3	22.8	21.5	21.3	19.5
2LJP (W/kg), mean±SD (%)	40.0±5.4 (100)	37.7±5.9 (94)	34.2±5.0 (86)*	30.8±5.8 (77)*	27.9±4.4 (70)*	24.2±5.8 (61)*	19.3±3.2 (48)*
Median	39.3	37.8	34.1	30.3	27.8	23.0	20.1
2LJvV (m/s), mean±SD (%)	2.2 (±0.2) (100)	2.1 (±0.2) (95)	2.0 (±0.2) (91)*	1.8 (±0.2) (84)*	1.7 (±0.2) (79)*	1.5 (±0.3) (70)*	1.3 (±0.2) (60)*
Median	2.2	2.1	2.0	1.9	1.7	1.5	1.3
CRTF (N/kg), mean±SD (%)	16.1±2.6 (100)	15.5±1.8 (96)	14.8±1.4 (92)*	14.2±1.3 (88)*	13.7±0.9 (85)*	13.4±1.4 (83)*	12.5±0.8 (77)*
Median	15.0	14.9	14.6	14.0	13.6	13.0	12.3
CRTP (W/kg), mean±SD (%)	12.1±1.9 (100)	12.1±2.0 (100)	12.1±1.7 (100)	10.9±1.9 (90)*	10.1±1.4 (84)*	8.7±2.1 (72)*	6.9±1.5 (57)*
Median	11.7	12.1	11.7	10.8	10.2	8.7	7.1
CRTvV (m/s), mean±SD (%)	1.1 (±0.2) (100)	1.1 (±0.2) (100)	1.1 (±0.1) (102)	1.0 (±0.2) (93)	1.0 (±0.1) (89)*	0.9 (±0.2 (77)*	0.8 (±0.1) (67)*
Median	1.1	1.1	1.1	1.0	1.0	0.8	0.7
	Men (n=353)						
	Age decade						
	20-29	**30-39**	**40-49**	**50-59**	**60-69**	**70-79**	**80+**
2LJF (N/kg), mean±SD (%)	26.4±3.4 (100)	24.9±3.8 (94)	24.1±4.1 (91)*	21.7±2.8 (82)*	22.1±2.8 (84)*	21.5±3.0 (81)*	21.9±3.0 (83)*
Median	26.6	23.9	22.9	20.9	21.9	21.3	22.4
2LJP (W/kg), mean±SD (%)	53.5±6.3 (100)	49.0±7.9 (92)*	44.4±5.5 (83)*	38.0±5.5 (71)*	35.2±6.1 (66)*	27.8±5.9 (52)*	26.1±4.2 (49)*
Median	52.4	47.6	43.9	37.1	35.2	27.4	25.7
2LJvV (m/s), mean±SD (%)	2.7 (±0.2) (100)	2.6 (±0.2) (96)*	2.5 (±0.2) (91)*	2.2 (±0.2) (83)*	2.1 (±0.2) (78)*	1.8 (±0.3) (65)*	1.7 (±0.2) (62)*
Median	2.7	2.6	2.5	2.2	2.1	1.8	1.7
CRTF (N/kg), mean±SD (%)	16.9±1.9 (100)	16.0±1.7 (96)	15.8±1.7 (95)*	15.0±1.6 (90)*	14.3±1.3 (86)*	13.5±1.3 (81)*	13.0±0.9 (78)*
Median	16.4	15.8	15.4	14.7	14.2	13.2	12.9
CRTP (W/kg), mean±SD (%)	15.5±3.0 (100)	14.8±2.1 (95)	15.2±2.3 (98)	13.4±2.1 (86)*	12.0±2.2 (78)*	10.2±2.3 (66)*	9.5±2.3 (61)*
Median	15.0	14.8	15.2	13.5	12.1	9.8	9.7
CRTvV (m/s), mean±SD (%)	1.4 (±0.2) (100)	1.3 (±0.2) (98)	1.4 (±0.2) (103)	1.3 (±0.2) (93)	1.2 (±0.2) (85)*	1.0 (±0.2) (74)*	1.0 (±0.2) (71)*
Median	1.4	1.4	1.4	1.3	1.2	1.0	1.0

*[†] %=percentage of mean of the youngest age group. * Significant age-related change compared to the third decade ($p<0.05$)*
2LJF=two leg jump force (N/kg), 2LJP=two leg jump power (W/kg), 2LJvV= two leg jump vertical velocity (m/s)
CRTF=chair rise test force (N/kg), CRTP=chair rise test power (W/kg), CRTvV= chair rise vertical velocity (m/s)

Table 2. Reference values for muscle performance by sex and age-decade.

		Intercept	Age	Sex	Age*age	Sex*age
2LJF (N/kg)	β	29.824	-0.171	-1.174	0.001	0.015
	SEM	1.114	0.043	0.747	0.000	0.013
	p	<0.0001	<0.0001	0.117	0.047	0.271
				R^2=0.18		
2LJP (W/kg)	β	63.006	-0.368	-16.691	-0.001	0.151
	SEM	1.948	0.076	1.307	0.001	0.023
	p	<0.0001	<0.0001	<0.0001	0.094	<0.0001
				R^2=0.71		
2LJvV (m/s)	β	2.8369	-0.0014	-0.6092	-0.0002	0.0039
	SEM	0.0739	0.0029	0.0496	0.0000	0.0009
	p	<0.0001	0.6160	<0.0001	<0.0001	<0.0001
				R^2=0.74		
CRTF (N/kg)	β	18.011	-0.050	-0.803	0.000	0.003
	SEM	0.538	0.021	0.360	0.000	0.006
	p	<0.0001	0.017	0.026	0.556	0.629
				R^2=0.36		
CRTP (W/kg)	β	13.951	0.103	-3.842	-0.002	0.025
	SEM	0.730	0.028	0.487	0.000	0.009
	p	<0.0001	<0.0001	<0.0001	<0.0001	0.005
				R^2=0.54		
CRTvV (m/s)	β	1.2009	0.0110	-0.2790	-0.0002	0.0011
	SEM	0.0604	0.0023	0.0403	0.0000	0.0007
	p	<0.0001	<0.0001	<0.0001	<0.0001	0.1164
				R^2=0.5		

**coding: men=0; women=1; 2LJF=two leg jump force (N/kg), 2LJP=two leg jump power (W/kg), 2LJvV=two leg jump vertical velocity (m/s), CRTF=chair rise test force (N/kg), CRTP=chair rise test power (W/kg), CRTvV=chair rise vertical velocity (m/s)*

Table 3. Association between muscle parameters and age and sex using linear regression analysis.

uated by adding an interaction term of sex*age. A p-value of $p<0.05$ was considered as significant. Scatter plots showing age and gender differences in the neuromuscular performance are presented. The statistical calculations were performed using the Statistical Analysis System SAS version 9.2 (SAS Institute Inc., Cary, North Carolina, USA).

Ethics

The present study was approved by the local ethics committee (EA4/095/05). Written informed consent was obtained from all participants before they were included into the study.

Results

Participants

771 individuals participated in the study. Leonardo measurements were available for 351 women and 353 men. The distribution of participants by age decades and sex and the anthropometric measures are presented in Table 1. With increasing age, height declined while weight and BMI increased in both sexes.

Age and sex effects

In all neuromuscular performance tests a significant decline across the life span in both women and men was observed (Table 2 and Table 3). While force decreased by about 20% from the third to the ninth decade, the decline of power was much higher, varying between 40-50% (Table 2). Age-related decline of 2LJ power and CRT force became significant in the age-group 40-49 in women while the decline of 2LJ force and CRT power became significant not until the sixth decade ($p<0.05$). In men however, the decline of 2LJ force and 2LJ power became significant already in the fifth decade, respectively in the fourth decade (Table 2).

The decline was linear for 2LJ power and for CRT force, whereas CRT power showed a curvilinear decline, which was modest or nonexistent in the under 40 year old groups, and thereafter a more robust decline was present (Figure 2d). For 2LJ force, the decline was linear for women and curvilinear for men showing no further decline after the age of 50 in men (quadratic term for age: women $p=0.48$, men $p=0.001$).

Men showed significantly higher values for all performance tests except for the 2LJ force values (Figure 2, Table 3). A sig-

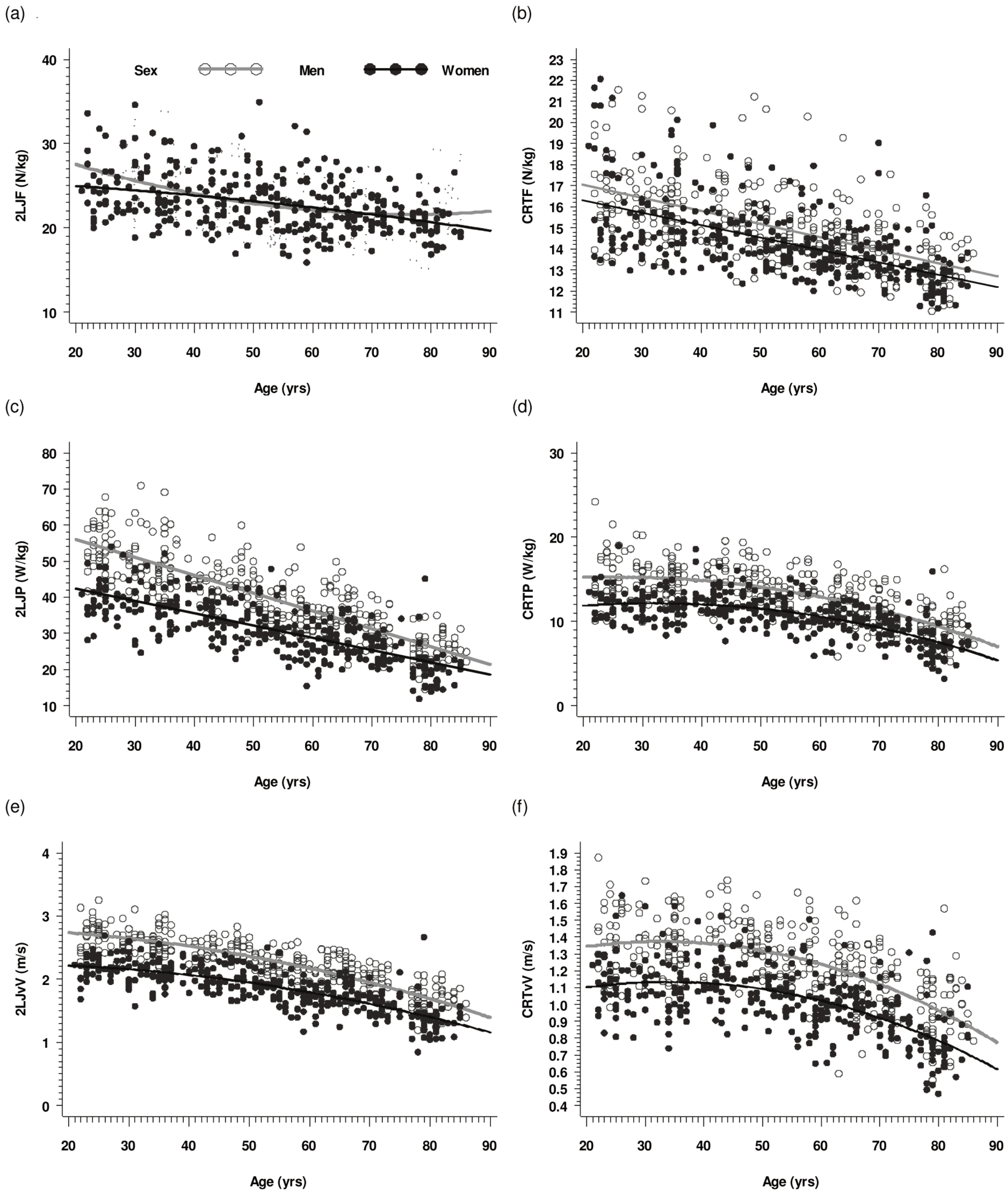

Figure 2. Regression plots of age and sex-related differences for the muscle parameters. Linear regression analysis of age and sex-related differences for the dependent variables (**a**) two leg jump force (2LJF), (b) chair rise test force (CRTF), (**c**) two leg jump power (2LJP), (**d**) chair rise test power (CRTP), (**e**) two leg jump vertical velocity (2LJvV) and (**f**) chair rise test vertical velocity (CRTvV).

nificant interaction between age and sex can be observed in both power parameters, which was confirmed by different slopes in the regression plots where men showed a steeper decline than women (Figure 2c, Figure 2d). Consequently, the differences between jumping and sit-to-stand power in men and women decreased with advancing age.

Analogue to mechanical power, vertical velocity in both tests declined by about 30-40%. Velocity was significantly higher in men than in women with a slightly steeper decline in the 2LJ test but not in the CRT. While the decline of 2LJvV was a continuous process across the life span in the CRTvV, a slight increase of 2-3% was observed until the fifth decade with a significant decrease in the seventh decade when compared to the young reference group (Table 2, Figure 2e, Figure 2f).

Results from the linear regression analysis are depicted in Table 3. Age and sex explained the variability of the power parameters to a much greater extent (power: R^2=0.54 to R^2=0.70; vertical velocity R^2=0.5 to R^2=0.74) than the force parameters (R^2=0.18 to R^2=0.36).

Discussion

The analyses presented in this article examine the influence of age and gender on neuromuscular performance. Confirming previous reports, this study demonstrates that neuromuscular function declines considerably with aging.

We observed a decline in 2LJ peak mechanical power of about 50% in both sexes from the third to the ninth decade which is in agreement with former cross-sectional studies applying the same jumping performance tests assessed with mechanography[28,30,34]. In contrast to the aforementioned studies, our reference values on peak mechanical power in countermovement jumps differ from the ones previously described in the literature. In a Japanese cross-sectional study[34] mean values for 2LJP adjusted for body mass are up to 15% higher in both sexes than the values reported in our study. These findings might result from a selection bias towards a physically more competent population, as participants in the Japanese study were recruited from a local gym and participants with a chair rise time (5 stands) of more than 10 seconds were excluded form the study. As Tsubaki et al report that the Japanese values did not differ significantly from the normative values of another German cross-sectional study with identical exclusion criteria[30], the observed differences are unlikely due to racial or ethnical differences. A small Greek cross-sectional study in women however, presents lower mean values on 2LJ power than our study[28]. As those women were recruited from a screening program on osteoporosis with a larger number of participants in the older age groups, the lower 2LJ power values might result from differences in the study population. No reference values on ground reaction force in countermovement jumps and chair rising across the life span using mechanography could be found in the literature.

In our study ground reaction force declined by about 20% in both sexes when the ninth decade is compared to the third. Previous cross-sectional studies using dynamometry describe a loss of knee extension force/ torque from age 20 to 80 varying between 30-60%[5-7,10,12]. However, the direct comparison between ground reaction force data and isometric force respectively torque data is problematic as the amount of force produced during a muscle contraction varies with the velocity of shortening. Thus, the force-velocity relationship dictates an optimal force and an optimal velocity at which maximal power can be developed. As our testing procedures focused on maximal power generation during a countermovement jump respectively five chair stands, the force values have to be interpreted as optimal values for the examined performance rather than maximal values. With isokinetic or isometric muscle testing procedures, higher force values will be obtained as speed of movement is slower or non-existent. However, these tests do not reflect everyday activity of the lower limb where body mass has to be moved against gravity.

Furthermore, an earlier study on vertical jumping performance suggests that vertical ground reaction force depends on countermovement magnitude and volitional effort[35]. A jumping pattern with the instruction "Jump as forceful as you can" is performed with a rather short eccentric countermovement and therefore with a short acceleration phase, a high vertical ground reaction force during lift off, which will finally result in lower jumping height and lower velocity. In contrast, a jumping pattern with the instruction "Jump as high as you can" leads to a longer countermovement with a longer acceleration phase and a lower, but longer force curve, resulting in a greater jumping height and a higher final velocity. As in our study the latter instruction was used the participants had to reduce the ground reaction force in order to increase velocity and jumping height.

Observational studies throughout a wide age range highlighted the importance of assessing power as it declines earlier in life and at a faster rate than force[5,26]. These findings support the observation of studies on muscle morphology which have shown that age-related loss of muscle function is associated with a loss of both slow and fast motor units, with a greater loss of fast motor units[36,37] and a decreased sliding speed of the myosin molecule[38]. As muscles and tendons act as a unit when transforming contractile forces to the skeleton, the velocity of force production is not only influenced by contractile properties but also by the mechanical properties of the tendons. Investigating the Achilles tendon *in vivo* using ultrasound, Narici et al report a decrease in the stiffness (-36%) and in the Young's modulus (-48%) between young and old adults[39]. In order to counteract the larger slack of the tendon, greater contractile efforts would be necessary to produce the same velocity as with a stiffer tendon. A loss of this compensation might contribute to the decrease in the velocity of force production[40].

As a limitation of our study one has to consider that individuals unable to walk without a walking aid were excluded from the study and generalised statements to persons with walking impairment living in the community or in nursing homes cannot be made. Hence, selection bias towards well functioning adults might have influenced the results, leading to an underestimation of the true decline in muscle function in the lower limb. Most recently, Zech et al reported a significant difference between non-frail and pre-frail older persons concerning muscle power[41]. Future research is needed to extend our results to pre-frail and frail older people and to confirm the applicability and safety of the force plate tests in this population.

A curvilinear association with an increased loss after 50 was observed in the CRT power results. However, given the generally high level of physical function in the study population, the use of the chair rise test might be of limited value, in particular in the younger adults as it might have induced a ceiling effect into this data set.

The cross-sectional design of the current study limits the ability to give a true estimate of age trends. Limited data from longitudinal studies present conflicting results. While some studies found a similar pattern for longitudinal decline of muscle force and torque as for cross-sectional decline[42,43], others report a smaller longitudinal decline[7,44,45] and one study notes a larger decline for force[46]. Importantly, most of those studies were relatively small, and only the study of Metter et al seems to be large enough (n=837 men in the follow-up) to allow for a generalisation[7]. The longitudinal decline in power from age 20 to 80 has been reported to be 10% greater than isometric force decline in men[7]. For women, no longitudinal decline in isometric force and power was described in the aforementioned investigation. However, the relatively small group of women in the follow-up visit (n=44) limits the scope of the analysis and the generalisability of the results. So far, no longitudinal data on mechanography have been published.

In conclusion, the present study found a decline of peak mechanical power from the third to the ninth decade of about 50% in both sexes using mechanography as a standardized assessment of motor performance. Our data provide researchers and clinicians with valuable reference data for physical performance tests across the adult life span. In line with previous research our findings confirm the importance of assessing neuromuscular power of the lower limb for understanding age-associated decline in functional performance and the development of sarcopenia. Physical performance using mechanography may provide a useful tool to monitor and evaluate proactive strategies for combating sarcopenia. Further research is necessary to translate the presented results into clinically meaningful endpoints, such as mobility limitation or fall risk in older people.

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