Rate of power development of the knee extensors across the adult life span: a cross-sectional study in 1387 Flemish Caucasians

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Abstract

A growing body of research in elderly populations suggests that the early phase of an explosive muscle contraction (i.e., $\leq 200\text{ms}$) may be more functionally relevant than peak values. However, age-related variation in early phase explosive strength have never been investigated across the full-adult life span. This cross-sectional study investigated the age-related changes in the rate of power development (RPD) and compared it to the changes in peak power (P_{peak}), both in terms of magnitude and onset, across the adult life span. Age-related declines in power and determinants of muscle power were compared between sexes.

1387 adults ($\text{♂}813$, $\text{♀}574$), aged 18-78 years, performed three maximal isoinertial knee extensor tests at 20% of their isometric maximum on a Biodex dynamometer. P_{peak} was calculated as the highest value and RPD as the linear slope of the power-time curve. Velocity (v) and torque (T) at P_{peak} were registered.

In both men and women, the decline in P_{peak} and RPD was already apparent from 40 years onwards. Annual percent decline rates were greater for RPD (-1.1% for men and -1.3% for women) than P_{peak} (-0.9% for men and -1.0% for women). Velocity at P_{peak} showed the lowest annual percent decline rates (-0.3% for men and -0.4% for women). Men performed better than women on all parameters (all $p < 0.001$). Velocity at P_{peak} tended to decline more in women than in men ($p = 0.065$).

To conclude, both knee extensor P_{peak} and RPD can be used to screen for age-related neuromuscular weaknesses at an early age. Both sexes seem equally susceptible to age-related declines in knee extensor power. In addition to traditional slow-speed resistance exercise, prevention strategies should include explosive exercises. Explosive exercises may be especially relevant in women, considering that they tend to decline more in the velocity component of muscle power.

Keywords

Rapid Force Production; Ageing; Muscle Function

Highlights

- Age-related declines in rate of power development exceed declines in peak power.
- Rate of power development and peak power are sensitive to age-related changes.
- Women tend to show greater age-related declines in velocity than men.

1. Introduction

Everyday activities, such as rising from a chair and climbing stairs, depend upon the lower limb muscles' ability to generate a certain amount of power [1, 2]. Consequently, reduced muscle power has been proposed as an important predictor of age-related deterioration in functional capacity [3, 4]. Progressive age-related declines in muscle power have been shown to exceed and even precede declines in maximal strength. While significant declines in maximal strength are typically reported from the age of 50 years onwards [1, 5, 6], the onset of decline in muscle power is observed from the age of 40 years [7]. Therefore, power might be more sensitive as a screening method for the detection of early deterioration of neuromuscular function than maximal strength.

In previous ageing research using large sample sizes and wide age ranges, muscle strength and/or power have typically been evaluated in terms of peak outputs [6-9]. However, a growing body of research in elderly populations suggests that the early phase of an explosive muscle contraction (i.e., ≤ 200 ms) may be more functionally relevant than peak values that need more time to be achieved (i.e. at least 300 to 500 ms in isometric conditions) [10-13]. This early phase of an explosive contraction is especially relevant in reactive motor tasks, such as balance recovery after tripping [14]. A typical outcome parameter that corresponds to this early phase (i.e., ≤ 200 ms) is the rate of force development (RFD) during a rapid voluntary isometric contraction [15]. Even though previous research on RFD during isometric contractions has already demonstrated marked differences between young and old adults [12], the functional value of isometric tests has often been questioned [16]. In daily activities, explosive force production is more often needed in activities that require concentric instead of isometric force. In addition, Tillin et al. (2012) suggested that the ability to use the muscle's explosive torque-producing capacity is influenced by contraction type, with explosive voluntary performance being superior during concentric than isometric contractions because of a greater neural drive to the agonist muscle (i.e. greater agonist root mean square EMG values normalized to maximal M-wave over the first 50 to 150 ms of contraction)[17]. Dynamic concentric contractions therefore seem more relevant than isometric contractions to evaluate early phase explosive

strength. This is particularly the case for isoinertial conditions, in which the load is fixed and accelerations can vary, because of their similarity to functional movements. Another important difference in force production between isometric and concentric contractions is that concentric force production is not only influenced by the muscle's ability to activate the contractile elements quickly and to transfer this force to the bone, but also by the force-velocity properties of the muscle [18]. Accordingly, concentric measurements differ from isometric measurements in the requirement for muscle shortening and provide different information.

In a recent paper, Van Driessche et al. (2018) evaluated both the rate of power development (RPD) and peak power by means of isoinertial knee-extension tests on a conventional Biodex dynamometer. By comparing an older population to a young reference group, they demonstrated that age-related differences in RPD exceeded differences in peak power, which emphasizes the added value of RPD in ageing research [19]. However, to our knowledge, no research has evaluated RPD across the adult life span. A thorough examination of the magnitude and timing of age-related changes in power development would provide us with valuable insights into the effect of ageing on neuromuscular function so that intervention strategies can be optimized. Given that power development is defined by both contractile force and contraction velocity, a comprehensive description of the impact of aging on these force-velocity components may yield crucial information to optimize detection and prevention strategies.

Currently, there is conflicting evidence in the literature as to whether age-associated changes in these components differ between ~~genders~~ sexes [6, 8, 20, 21]. Interestingly, Edwén et al. (2014) showed that middle-aged (35-55 years) and older (>65 years) women demonstrate lower leg muscle power during a countermovement jump compared to men, mainly due to a reduced velocity component rather than a reduced force component [22]. This finding may have important implications in regards to functional decline in women, but should be confirmed in different settings.

Therefore, the aim of the present study was to investigate the age-related decline in RPD and to compare this decline to the decline in peak power, both in terms of magnitude and onset, across the adult life span. In addition, age-related declines in power and determinants of muscle power were compared between sexes.

2. Methods

2.1. Subjects

This cross-sectional study is part of a Flemish longitudinal study of which the sampling procedure was previously described in detail by Matton et al. [23]. Subjects consisted of 18- to

78-year-old adults randomly selected within the community in Flanders, Belgium. Data collection took place between October 2002 and April 2004. All subjects went through a medical examination, anthropometric measurements, physical performance tests, and physical activity and health-related questionnaires. The exclusion criteria have been previously reported in detail [24]. Briefly, subjects were excluded in the case of cardiovascular disease or acute thrombosis, recent surgery, neuromuscular disease, infection or fever, diabetes and/or pregnancy. The current study focused on measurements of muscle strength, power and functional performance. Data of 813 men and 574 women, aged 18 to 78 years, were included in the analyses. The study was approved by the University's Human Ethics Committee in accordance with the declaration of Helsinki. All subjects provided written informed consent.

2.2. *Outcome measurements*

The outcome measurements have been previously described [24]. Below, a concise overview is provided and procedures are further clarified where necessary.

2.2.1. Anthropometry

Body height (m) was measured to the nearest millimeter using a Holtain stadiometer (Holtain, Crymych, UK) and body mass (kg) was measured to the nearest 0.1 kg using a digital scale (Seca 841, Seca GmbH, Hamburg, Germany). Body Mass Index (BMI) was calculated as mass (kg) divided by squared height (m²).

2.2.2. Muscle strength and power

Procedure – Force-velocity characteristics of the knee extensors were measured using a standardized protocol on a Biodex Medical System 3[®] dynamometer (Biodex Medical Systems, Shirley, New York, USA). Positioning of the subjects was fixed according to standardized procedures, as reported previously [6]. All tests were performed unilaterally on the right leg. The protocol consisted of two tests, performed in the following order: isometric followed by isoinertial tests. The best performances, i.e. the repetition with the highest torque for the isometric test and the highest velocity for the isoinertial test, ~~was~~ were used for further analysis. Isometric knee extensor strength was assessed at a knee joint ~~flexion~~ angle of 90° (with 0° corresponding to full extension). Subjects were instructed to extend their leg as hard as possible for 5 seconds. The test was conducted twice, separated by a 20-second rest interval.

Ballistic isoinertial tests were performed at a constant load of 20% of the maximal isometric strength at a 90° knee joint angle. Subjects were instructed to extend their leg as fast as possible from a knee joint angle of 90° to 160° and passively return to the starting position. Three repetitions were performed.

Signal processing - Torque and velocity signals were sampled at 100Hz and processed offline using Matlab (The Mathworks Natick, USA). For the isometric test, the maximal voluntary contraction (MVC, Nm) was defined as the highest value of the torque-time curve. For the isoinertial test, instantaneous power (watt) was calculated as the product of torque (Nm) and velocity (rad/s) throughout the movement. Peak power was identified as the highest value of the power-time curve (P_{peak} , w), together with its constituting components, namely torque (T at P_{peak} , Nm) and velocity (v at P_{peak} , °/s). The knee joint angle at which peak power was reached, was defined as the angle at P_{peak} (°). Time to peak power (ttP_{peak} , s) was defined as the time from the onset of the movement until peak power was reached. The rate of power development was determined as the linear slope of the power-time curve from the onset of the movement until peak power was reached (RPD; $\Delta\text{power}/\Delta\text{time}$; watt/s). The onset of the movement was defined as the point where the acceleration reached a threshold of 150°/s². The reliability of this methodology in a sample of 63 older adults (65 – 85 years) was excellent; the ICC and CV(%) ranged from 0.90 to 0.98 and from 5% to 9% for all variables [25].

2.3. Statistical analyses

Statistical analyses were performed using SPSS software version 24 (SPSS Inc., Chicago, IL). The level of significance was set at $p < 0.05$. Subjects were divided into six distinct age categories (per decade). Descriptive statistics per age category were represented as means and standard deviations. One-way analysis of covariance (ANCOVA) with Bonferroni post hoc tests were used to compare age categories within each ~~gender~~-sex separately. Body mass was used as a covariate.

To evaluate and compare average age-related decline rates (in % per year) in MVC, P_{peak} , T at P_{peak} , v at P_{peak} and RPD (dependent variables) within and between sexes, dependent variables were first log-transformed (natural log). A log-transformation of the dependent variable in regression models allows interpreting exponentiated β coefficients as percent changes [26]. Scatterplots with log-transformed parameters (P_{peak} , T at P_{peak} , v at P_{peak} , RPD) on the y-axis and age on the x-axis were used to visualize the data. A line of best fit was added to the

scatterplots according to the loess smoothing method (Kernel Epanechnikov function, 80% of points to fit).

Linear regression analyses with the abovementioned log-transformed parameters as dependent variable and age as independent variable were performed within sexes separately. Body mass was introduced as a covariate in the regression analyses. Regression slopes were interpreted as age-related decline rates (in %). Differences in regression slopes between dependent variables (MVC, P_{peak} , T at P_{peak} , v at P_{peak} , RPD) were evaluated by comparison of 95% confidence intervals [22]. As previous research has shown that age and strength or power have a nonlinear relationship [6], polynomial regression models were used in addition to the abovementioned linear regression models, including body mass, age and age² as independent variables.

Analyses of covariance with the abovementioned log-transformed parameters as dependent variables, ~~gender~~-sex as the independent variable and age and body mass as covariates were performed. The main effects of ~~gender~~-sex and age by ~~gender~~-sex interaction effects were investigated.

3. Results

Subject characteristics are described in Tables 1 and 2. Outcomes of ANCOVA's with Bonferroni post hoc tests to compare age categories for men and women separately are presented in Tables 1 and 2. Figure 1 represents scatterplots to visualize age-related changes in P_{peak} , T at P_{peak} , v at P_{peak} and RPD. All parameters, except for angle at P_{peak} , showed an age-related deterioration (all $p < 0.05$, Tables 1 and 2, Figure 1). In both men and women, the decline in P_{peak} and RPD was already apparent in the age group of 40-50 years. The decline in torque at P_{peak} became significant from the age group of 40-50 years in men and 50-60 years in women, whereas the decline in velocity at P_{peak} was apparent in the age group of 40-50 years in women and 60-70 years in men (Tables 1 and 2). Time to P_{peak} only showed significant differences in the age group of 60-70 years when compared to younger age groups. Visual inspection of the scatterplots with the line of best fit in Figure 1 confirmed that most parameters dropped below normal values for a young reference group between the ages of 40 to 50 years. Results of linear and quadratic regression models with log-transformed MVC, P_{peak} , T at P_{peak} , v at P_{peak} and RPD as dependent variables and age and body mass as independent variables are presented in Tables 3 and 4. Age was a significant predictor of all parameters (R^2 ranged from 0.049 to 0.165 in men and from 0.059 to 0.155 in women) (all $p < 0.05$). Annual percent decline rates were greatest for RPD (-1.1% for men and -1.3% for women), while v at P_{peak} showed the lowest annual percent decline rates (-0.3% for men and -0.4% for women). P_{peak} (-0.9% for men

and -1.0% for women) seemed to decline more than MVC (-0.7% for men and -0.6% for women), although 95% confidence intervals of the β -coefficients overlapped. In addition, the quadratic age term was significant in all regression models (all $p < 0.05$).

To identify ~~gender~~sex differences in age-related declines in MVC, P_{peak} , T at P_{peak} , v at P_{peak} and RPD, ANCOVA with ~~gender~~sex as the independent variable and age and body mass as covariates were performed and age by ~~gender~~sex interaction effects were evaluated. There was a significant main effect of ~~gender~~sex, with men performing better than women on all parameters (all $p < 0.001$, Table 5). However, no significant age by ~~gender~~sex effects were found, although a trend was apparent for v at P_{peak} . In this parameter, women tended to decline more than men ($p = 0.065$).

Table 1. Subject characteristics and neuromuscular performance in **men** by age group. Data are presented as means $\pm$ SD.

	18-30 years	30-40 years	40-50 years	50-60 years	60-70 years	>70 years	Age group difference*
<i>n</i> (range)	87-88	152-154	365-371	97-98	87-89	14	
Age (years)	23.1 $\pm$ 3.6	36.6 $\pm$ 2.7	45.2 $\pm$ 2.6	55.7 $\pm$ 2.7	64.4 $\pm$ 2.7	73.4 $\pm$ 2.7	
Body mass (kg)	73.1 $\pm$ 11.6	80.0 $\pm$ 11.7	81.2 $\pm$ 10.3	78.9 $\pm$ 9.1	79.6 $\pm$ 9.7	75.5 $\pm$ 11.1	
Body height (cm)	178.0 $\pm$ 6.7	179.0 $\pm$ 6.3	177.7 $\pm$ 6.0	173.8 $\pm$ 6.0	172.5 $\pm$ 6.9	169.8 $\pm$ 5.2	
BMI (kg/m ²)	23.0 $\pm$ 3.2	24.8 $\pm$ 3.0	25.7 $\pm$ 2.9	26.1 $\pm$ 2.7	26.7 $\pm$ 2.6	26.2 $\pm$ 3.5	
MVC (Nm)	235.0 $\pm$ 61.5	237.7 $\pm$ 52.2	<u>233.2 $\pm$ 53.5</u>	210.1 $\pm$ 38.1	189.0 $\pm$ 40.8	157.2 $\pm$ 43.1	a > c; abc > def; d > ef
P _{peak} (watt)	515.2 $\pm$ 121.0	540.2 $\pm$ 121.6	<u>509.2 $\pm$ 111.1</u>	452.9 $\pm$ 91.3	390.2 $\pm$ 83.0	304.7 $\pm$ 74.4	b > c; abc > def; d > ef
T at P _{peak} (Nm)	79.5 $\pm$ 14.1	82.2 $\pm$ 13.3	<u>78.2 $\pm$ 12.6</u>	71.6 $\pm$ 9.9	65.2 $\pm$ 9.4	57.4 $\pm$ 9.1	ab > cdef; c > def
v at P _{peak} (°/s)	368.7 $\pm$ 40.7	374.7 $\pm$ 44.9	371.0 $\pm$ 41.4	361.1 $\pm$ 45.6	<u>340.9 $\pm$ 43.5</u>	302.8 $\pm$ 52.1	abcd > ef
Angle at P _{peak} (°)	58.1 $\pm$ 5.8	58.2 $\pm$ 6.8	56.7 $\pm$ 6.2	56.7 $\pm$ 6.0	57.0 $\pm$ 6.9	61.6 $\pm$ 5.2	≠
ttP _{peak} (s)	0.169 $\pm$ 0.025	0.164 $\pm$ 0.041	0.168 $\pm$ 0.036	0.174 $\pm$ 0.026	<u>0.182 $\pm$ 0.036</u>	0.178 $\pm$ 0.042	bc > e
RPD (watt/s)	3150.7 $\pm$ 1016.2	3448.6 $\pm$ 1093.6	<u>3165.0 $\pm$ 1017.1</u>	2676.2 $\pm$ 781.3	2224.9 $\pm$ 704.4	1795.8 $\pm$ 634.0	b > c; abc > def; d > ef

*Results of ANCOVA and Bonferroni post hoc with age as independent variable and body mass as covariate. To visualize the starting point of

the decline, means are underlined in the age group where the performance is significantly lower compared to a younger age group. a = age group

18-30 years, b = age group 30-40 years, etc.

BMI = body mass index; MVC = maximal voluntary contraction (isometric); P_{peak} = peak power; T = torque; v = velocity; ttP_{peak} = time to peak

power; RPD = rate of power development

Table 2. Subject characteristics and neuromuscular performance in **women** by age group. Data are presented as means $\pm$ SD.

	18-30 years	30-40 years	40-50 years	50-60 years	60-70 years	>70 years	Age group difference*
<i>n</i> (range)	47-48	151-152	244-249	79-81	35-37	7	
Age (years)	23.1 $\pm$ 3.5	37.0 $\pm$ 2.5	43.6 $\pm$ 2.7	54.6 $\pm$ 3.1	63.7 $\pm$ 2.5	72.3 $\pm$ 2.1	
Body mass (kg)	62.0 $\pm$ 8.2	65.2 $\pm$ 11.0	65.4 $\pm$ 10.6	66.2 $\pm$ 9.5	63.4 $\pm$ 12.0	61.6 $\pm$ 7.0	
Body height (cm)	166.7 $\pm$ 6.7	165.3 $\pm$ 5.7	165.5 $\pm$ 5.4	162.5 $\pm$ 5.6	158.9 $\pm$ 7.9	155.2 $\pm$ 4.8	
BMI (kg/m ²)	22.3 $\pm$ 2.5	23.8 $\pm$ 3.8	23.9 $\pm$ 3.8	25.1 $\pm$ 3.4	25.1 $\pm$ 4.5	25.7 $\pm$ 3.5	
MVC (Nm)	140.5 $\pm$ 30.6	139.3 $\pm$ 29.4	140.5 $\pm$ 31.3	<u>128.6 $\pm$ 30.5</u>	107.1 $\pm$ 28.8	104.9 $\pm$ 9.4	c > d; ad > ef; bc > e
P _{peak} (watt)	327.2 $\pm$ 72.6	329.7 $\pm$ 69.4	<u>307.2 $\pm$ 65.2</u>	273.5 $\pm$ 65.0	223.3 $\pm$ 61.1	190.6 $\pm$ 25.9	ab > c; abc > def; d > ef
T at P _{peak} (Nm)	55.8 $\pm$ 8.5	55.6 $\pm$ 7.7	54.0 $\pm$ 8.0	<u>50.2 $\pm$ 8.0</u>	42.6 $\pm$ 8.3	40.3 $\pm$ 3.2	abc > def; d > ef
v at P _{peak} (°/s)	333.5 $\pm$ 37.9	337.9 $\pm$ 40.8	<u>324.5 $\pm$ 40.9</u>	309.5 $\pm$ 36.5	296.4 $\pm$ 39.9	270.5 $\pm$ 26.2	b > c; ab > def; c > ef
Angle at P _{peak} (°)	59.2 $\pm$ 5.0	58.6 $\pm$ 6.4	59.1 $\pm$ 6.4	59.6 $\pm$ 6.5	58.4 $\pm$ 5.8	62.2 $\pm$ 3.2	†
ttP _{peak} (s)	0.187 $\pm$ 0.029	0.183 $\pm$ 0.030	0.185 $\pm$ 0.034	0.192 $\pm$ 0.029	<u>0.208 $\pm$ 0.035</u>	0.206 $\pm$ 0.021	abc > e
RPD (watt/s)	1815.5 $\pm$ 590.9	1846.1 $\pm$ 496.6	<u>1753.1 $\pm$ 862.9</u>	1456.1 $\pm$ 420.3	1122.4 $\pm$ 410.4	932.9 $\pm$ 186.1	b > c; abc > def; d > e

*Results of ANCOVA and Bonferroni post hoc with age as independent variable and body mass as covariate. To visualize the starting point of

the decline, means are underlined in the age group where the performance is significantly lower compared to a younger age group. a = age group

18-30 years, b = age group 30-40 years, etc.

BMI = body mass index; MVC = maximal voluntary contraction (isometric); P_{peak} = peak power; T = torque; v = velocity; ttP_{peak} = time to peak

power; RPD = rate of power development

Figure 1. Scatterplot representing the age-related decline in peak power (P_{peak}), rate of power development (RPD), torque at peak power ($T \text{ at } P_{\text{peak}}$) and velocity at peak power ($v \text{ at } P_{\text{peak}}$) for $N = 1387$ adults. Lines represent the best fit of data according to the loess smoothing method (Kernel Epanechnikov function, 80% of points to fit). Men are visualised by bullets (o) and solid line, women by asterik (*) and dashed line.

Table 3. Results of linear and quadratic regression analyses with age, age x age, and body mass as independent variables in **men** ($n = 808$ -810).

	Linear regression					Quadratic regression				
		β -coefficients (95% COI)	R ² change	Adj. model R ²		β -coefficients (95% COI)	R ² change	Adj. model R ²		
MVC	(Constant)	4.973 (4.852 – 5.095)		0.227	(Constant)	4.706 (4.536 – 4.875)				0.244
	BM	0.009 (0.008 – 0.010)	0.126		BM	0.008 (0.007 – 0.010)	0.126			
	Age	-0.007 (-0.08 – -0.005)	0.103		Age x Age	-0.0002 (-0.0002 – -0.0001)	0.115			
P _{peak}					Age	0.009 (0.002 – 0.016)	0.005			
	(Constant)	5.857 (5.732 – 5.982)		0.261	(Constant)	5.485 (5.313 – 5.656)				0.295
	Age	-0.009 (-0.010 – -0.007)	0.131		Age x Age	-0.0002 (-0.0003 – -0.0002)	0.162			
T at pP	BM	0.009 (0.007 – 0.010)	0.132		BM	0.008 (0.006 – 0.009)	0.122			
					Age	0.013 (0.006 – 0.020)	0.011			
	(Constant)	4.054 (3.971 – 4.138)		0.299	(Constant)	3.842 (3.727 – 3.957)				0.320
v at P _{peak}	BM	0.007 (0.006 – 0.008)	0.135		Age x Age	-0.0001 (-0.0002 – -0.00008)	0.162			
	Age	-0.006 (-0.007 – -0.005)	0.165		BM	0.006 (0.005 – 0.007)	0.155			
					Age	0.006 (0.001 – 0.011)	0.005			
RPD	(Constant)	5.850 (5.779 – 5.922)		0.074	(Constant)	5.691 (5.592 – 5.789)				0.096
	Age	-0.003 (-0.003 – -0.002)	0.049		Age x Age	-0.0001 (-0.0001 – -0.00006)	0.063			
	BM	0.002 (0.000 – 0.003)	0.027		BM	0.002 (0.001 – 0.002)	0.025			
					Age	0.007 (0.002 – 0.011)	0.011			
	(Constant)	7.614 (7.423 – 7.805)		0.183	(Constant)	7.121 (6.857 – 7.384)				0.212
	Age	-0.011 (-0.013 – -0.009)	0.098		Age x Age	-0.0003 (-0.0004 – -0.0002)	0.122			

BM	0.010 (0.008 – 0.013)	0.087	BM	0.009 (0.007 – 0.011)	0.080
			Age	0.017 (0.007 – 0.028)	0.010

All dependent variables were log-transformed to allow interpreting exponentiated β -coefficients as percent changes. BM = body mass; MVC = maximal voluntary contraction (isometric); P_{peak} = peak power; T = torque; v = velocity; RPD = rate of power development

Table 4. Results of linear and quadratic regression analyses with age, age x age, and body mass as independent variables in **women** ($n = 563-570$).

Quadratic regression						
Linear regression						
	β -coefficients (95% COI)	R ² change	Adj. model R ²	β -coefficients (95% COI)	R ² change	Adj. model R ²
MVC	(Constant)	4.694 (4.555 – 4.834)	0.136	(Constant)	4.333 (4.095 – 4.571)	
	BM	0.007 (0.005 – 0.009)	0.080	BM	0.006 (0.005 – 0.008)	0.080
	Age	-0.006 (-0.008 – -0.004)	0.059	Age x Age	-0.0002 (-0.0003 – -0.0001)	0.070
P _{peak}	(Constant)	5.664 (5.522 – 5.805)	0.236	Age	0.012 (0.002 – 0.022)	0.009
	Age	-0.010 (-0.012 – -0.008)	0.155	(Constant)	5.210 (4.971 – 5.449)	
	BM	0.007 (0.005 – 0.009)	0.081	Age x Age	-0.0003 (-0.0004 – -0.0001)	0.178
T at pP	(Constant)	3.883 (3.793 – 3.974)	0.250	BM	0.007 (0.005 – 0.009)	0.077
	Age	-0.006 (-0.007 – -0.005)	0.142	Age	0.012 (0.003 – 0.022)	0.008
	BM	0.005 (0.004 – 0.007)	0.111	(Constant)	3.581 (3.428 – 3.734)	
v at P _{peak}	(Constant)	5.828 (5.747 – 5.908)	0.096	Age x Age	-0.0002 (-0.0002 – -0.0001)	0.165
	Age	-0.004 (-0.005 – -0.003)	0.082	BM	0.005 (0.004 – 0.006)	0.107
	BM	0.002 (0.001 – 0.003)	0.017	Age	0.009 (0.002 – 0.015)	0.010
RPD	(Constant)	7.388 (7.129 – 7.583)	0.187	(Constant)	5.753 (5.683 – 5.824)	
				Age x Age	-0.00004 (-0.00006 – -0.00003)	0.092
				BM	0.002 (0.001 – 0.003)	0.016
				Age	+	+
				(Constant)	6.732 (6.402 – 7.063)	0.217

Age	-0.013 (-0.015 – -0.010)	0.132	Age x Age	-0.0004 (-0.001 – -0.0002)	0.155
BM	0.008 (0.006 – 0.011)	0.058	BM	0.008 (0.005 – 0.010)	0.055
			Age	0.020 (0.007 – 0.034)	0.012

All dependent variables were log-transformed to allow interpreting exponentiated β -coefficients as percent changes. BM = body mass; MVC = maximal voluntary contraction (isometric); P_{peak} = peak power; T = torque; v = velocity; RPD = rate of power development

Table 5. Results (p-values) of ANCOVA with sexgender as independent variable and age and body mass as covariates.

	Main effect of <u>gender</u> sex	Age by <u>gender</u> sex interaction
		effect
MVC	<0.001	0.415
P _{peak}	<0.001	0.200
T at P _{peak}	<0.001	0.728
v at P _{peak}	<0.001	0.065
RPD	<0.001	0.310

All dependent variables were log-transformed. MVC = maximal voluntary contraction (isometric); P_{peak} = peak power; T = torque; v = velocity;
RPD = rate of power development

4. Discussion

The current study is the first to investigate isoinertial knee extensor rate of power development across the full-adult life span in a large sample of adults. In addition, declines in peak power and its force-velocity components were assessed and compared between sexes. The main findings were: (1) the age-related decline in RPD is greater in magnitude than the decline in peak power, (2) RPD and P_{peak} appear to be sensitive enough to identify age-related differences at an early age (from 40 years onwards), (3) declines in torque precede declines in velocity in men, whereas the opposite is true for women, (4) women tend to show greater declines in velocity than men.

As expected, the age-related percent decline rates in peak power (-0.9% - -1.0% per year) across the adult life span were greater than the decline in isometric peak torque (-0.7% - -0.6% per year) in both sexes. The magnitude of that decline in power, i.e. about 1% per year, is similar to previous reports on knee extensor peak power decline over a similar age range [7, 27]. The greater decline in power in comparison to strength can be attributed to a combination of single-fiber changes, such as a decreased maximum shortening velocity, a preferential denervation and atrophy of type II fibers, and changes in neural drive [28-30]. All together, these age-related changes have been shown to result in a slowing of muscles [28, 30].

Considering this age-related slowing of muscles, a growing body of research has underlined the importance of the early phase of an explosive contraction in ageing research [10, 12, 14, 31]. Therefore, the current study evaluated the rate of power development in addition to peak power. As the main and novel finding, this study showed that age-related differences in knee extensor RPD exceed differences in knee extensor peak power over the full-adult life span. More specifically, RPD declined at a rate of -1.1% and -1.3% compared to -0.9% and -1.0% for peak power in men and women, respectively. Although this steeper decline could not be confirmed statistically by comparing 95% confidence intervals of the regression slopes, the age-related increase in the time to peak power suggests that RPD might provide a more complete picture of neuromuscular ageing than peak power. This confirms our previous findings [19], where we were able to show larger differences in RPD than in peak power between a group of young (20-30 years) and older adults (60-80 years).

At this point, we can only speculate on the relative contribution of neural and muscular determinants of RPD and peak power. Theoretically, RPD might be more influenced by muscle-tendon unit stiffness than peak power. Previous research has demonstrated a positive relationship between isometric RFD and connective tissue stiffness, indicating that rapid muscle actions rely at least partly on effective force transmission from the contractile elements

to the skeleton [32]. The recoil of the tendon occurs later in a fast concentric movement [33] and might therefore affect peak power more than RPD. In addition, it has been suggested that the early phase (first 50-75 ms) of a rapid isometric contraction is affected by an interaction between the rate of activation and fiber type [15, 34]. The primary determinants of explosive force production change throughout the time course of a contraction, with contractile properties becoming more relevant in later stages of a contraction (75-150 ms) [35]. Although the difference might be subtle, RPD might rely more on the increase of muscle activation at the onset of the contraction than peak power, which might explain the steeper decline during ageing. It is however important to note that we used explosive dynamic contractions instead of isometric contractions, which may involve different activation strategies [17]. In addition, isoinertial tests demand a certain amount of pre-tension (e.g. 20% of the individual maximal strength) prior to the onset of the measurement, which may influence motor unit discharge patterns [36]. Therefore, caution is advised when applying the findings of isometric contractions to dynamic contractions.

Isoinertial contractions are preferred over isometric contractions due to their functional relevance. An additional advantage of isoinertial tests over isometric tests is the lower incidence of a Valsalva maneuver and consequently the smaller acute elevation in blood pressure [37], resulting in a more comfortable and safer test method for elderly individuals. Another difference between concentric and isometric tests is that explosive dynamic contractions are much more influenced by the shortening characteristics of the muscle than isometric contractions, while they are both influenced by activation rate, rate of subsequent contractile force production and rate of force transfer. Therefore, dynamic and isometric tests provide different information and have their own unique value in research and (clinical) practice. We should additionally acknowledge the complexity of dynamic isoinertial contractions with regard to the torque-angle-velocity relationship. At this point, the potential confounding influence of age-related changes in the torque-angle relationship of the knee extensors on RPD is unclear and goes beyond the scope of this manuscript. Ageing is accompanied by decreases in fascicle lengths; [38]. Together with other structural age-related changes in the muscle-tendon unit, such as decreased tendon stiffness, this might result in a shift in the torque-angle relationship, even though there appears to be very little evidence that fascicle length ~~changes~~ influences the optimal angle of force production [38, 39]. Nevertheless, our data show that there is no age-related change in the angle of peak power, which is consistent with the findings of Van Driessche et al. 2018 [19]. Therefore, we can rule out that the longer time needed to reach peak

power in older adults is a consequence of a shift in the angle of peak power compared to younger adults.

To identify outcome parameters that are most feasible to screen for early age-related declines in neuromuscular function, the onset of the declines are of major importance, in addition to their magnitude. To evaluate the onset of decline, data were plotted and the best fit of data was visualized so that the time course of declines could be interpreted. In addition, age groups (per decade) were compared to identify significant between-group differences. In agreement with previous research of Kostka [7], peak power dropped significantly after the fourth decade in both sexes, which confirms its potential as a screening tool to identify early age-related neuromuscular declines. None of the other outcome parameters (i.e. isometric peak torque, T or v at peak power) seems able to detect declines from 40 years onwards in both sexes, except for RPD. Similar to the onset of the decline in power, RPD showed a systematic decline from 40 years onwards. Considering that measurements of RPD are more prone to variability and need more detailed analyses than peak power, our recommendation would be to use peak power as a screening tool for age-related deficits in neuromuscular function.

Power is defined by both force and velocity and thus entails the combination of contractile properties of the muscle and its neural activation. This combination makes it sensitive to age-related changes in either component. However, to optimize prevention strategies, a better understanding of the impact of aging on both force-velocity components may be crucial. In addition, a more detailed analysis of these components might detect sex differences in the ageing process, providing the unique opportunity to develop sex-specific exercise guidelines. In line with previous research, men were stronger, faster and more powerful than women [21]. These sex differences were more pronounced in the force component as compared to the velocity component. For instance, in the age group of 40-45 years, T at P_{peak} was 31% higher and v at P_{peak} was 13% faster in men compared to women. Previous research came to similar conclusions in multi-joint isoinertial tests [21], but our results are in contrast with previous findings in stretch-shortening cycle leg extension power tests [22, 40]. This discrepancy is likely due to differences in contraction types and testing procedures.

Interestingly, men and women seem to experience similar annual percent decline rates in peak power and RPD. These declines seem more driven by declines in force-generating capacity (-0.6%) compared to declines in the velocity component (-0.3% - -0.4%) in both sexes, again in agreement with previous findings in multi-joint tests [21, 41]. Research on muscle architectural changes with ageing already demonstrated that the cross-sectional area of the muscles (i.e.,

sarcomeres in parallel, force-generating capacity) decrease more than their fascicle length (i.e., sarcomeres in series, shortening velocity), which might explain our findings [42].

Remarkably, there appears to be a sex difference in the onset of decline in the force and velocity component of muscle power. The onset of decline in velocity is clearly identified at an earlier stage in women than in men, while the opposite seems true for the force component (albeit less obvious). The additional finding that velocity tends to decline more in women across the entire adult-life span (18-78 years) might explain the higher fall incidence rates previously reported in women compared to men (<80 years) [43]. To the authors' knowledge, this is the first study that compared the onset of decline in the force and velocity component of muscle power between sexes. Although velocity-oriented training in addition to traditional strengthening exercise is greatly needed in both sexes, our data underline the importance of initiating high-speed exercise interventions in women at relatively young age (i.e., 40-50 years).

A potential methodological limitation of the present study is its cross-sectional design, which may be confounded by interindividual differences, and patterns of decline may differ in longitudinal comparisons. Given the limited number of individuals over 70 years of age, we were not able to explore whether the age-related decline rates accelerate after a certain age. As visualized in the scatterplots in Figure 1, muscle power starts to decline from the fourth decade onwards. Annual percent decline rates were analyzed over the entire age range (18-78 years), which resulted in an overestimation of the magnitude of decline in young (< 40 years of age) and an underestimation in older (> 40 years of age) adults. For instance, percent decline rates for P_{peak} and RPD increased to -1.4% and -1.8% in men and to -1.3% and -1.8% in women when analyzed from 40 years onwards. We should acknowledge that age and power have a nonlinear relationship, as demonstrated by the significance of the quadratic age term, and the average decline rates are therefore a simplification of the real data. Even in the quadratic models, age was only able to explain up to 18% of the variance in power or RPD over the full age range. This is probably due to the finding that power development is quite stable (or even increases) from 20 years to about 40-45 years of age. Very low or non-significant relationships between age and power in men and women below 45 years of age ($r = 0.04$ and $r = -0.12$ in men and women respectively, not reported in the results section) confirm that age is not a good predictor of power development in 'early' adulthood. Our data seem to indicate that factors other than age have a marked influence on power development, such as genetics and environmental or lifestyle factors, including rates and types of exercise training. Power development seems to be maintained in some 70 year olds, but at this point, we can only speculate on the underlying reasons. Another limitation is that isoinertial knee extensor power was only evaluated at one

specific load (i.e., 20% of the isometric maximum), so we were not able to plot force-velocity or power-velocity relationships. However, Van Driessche et al. 2018 ~~already showed~~ has shown that isolated knee extensor power at 20% load was more related to functional capacity (i.e., walking, timed-up-and-go, stair climbing, all $r > 0.60$) in older community-dwelling older adults than similar tests at higher loads, which justifies the use of this particular load [19].

To conclude, this study investigated the onset and magnitude of the decline in knee extensor peak power and RPD in a large sample ($N = 1387$) across a wide age range (18-78 years). The main and novel finding is that RPD declines more than peak power, most likely because it provides a more complete picture of the components of neuromuscular ageing. The onset of decline in RPD and peak power is visible from the age of 40 in both sexes, underlining the potential of these parameters to screen for age-related weaknesses at an early age. Both sexes seem equally susceptible to age-related declines in knee extensor power. Prevention strategies should therefore combine traditional slow-speed resistance exercise with explosive exercises. Explosive exercises may be especially relevant in women, considering that they tend to decline more in the velocity component of muscle power.

Conflict of interest

The authors declare no conflicts of interest.

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