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Knee extension rate of torque development and peak torque: associations with lower extremity function

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Abstract

Background With aging, the ability to generate muscle force decreases, contributing to declines in physical functions such as walking. While most studies assess muscle force by peak torque, the rate of torque development (RTD) reflects a dynamic component of muscle performance that is important for physical function. Using data from the Baltimore Longitudinal Study of Aging, we assessed whether RTD adds significantly to peak torque in associations with lower extremity performance. If so, RTD may help identify weak older adults for screening and intervention.

Methods We assessed associations of RTD and peak torque with physical performance independent of demographics, BMI, body composition, and each other in 1089 Baltimore Longitudinal Study of Aging participants (49.7% women; aged 26 to 96 years; women, 64.0 ± 13.8 years; men, 68.4 ± 14.4 years). Peak torque was assessed by isometric and 30 deg/s isokinetic knee extension tests. Peak RTD was operationalized as the maximum torque-time slope among successive 50 ms epochs over the first 3 s of a test of knee extension isometric strength, with the knee joint positioned at 120 deg of flexion. A battery of lower extremity performance tests included gait speed during a 6 m walk at usual and fast pace (6 m usual and fast), time to complete a 400 m walk at fast pace (400 m), distance covered in a 2.5 min walk at normal pace (2.5 min), time to complete 5 and 10 chair stands, and two summary tests of lower extremity performance. Sex-stratified generalized linear regression models were adjusted for age, race, BMI, appendicular lean mass, and whole body fat mass.

Results In men, independent of either measure of peak torque and cofactors, RTD was a significant ($P < 0.05$) predictor of all lower extremity performance tests except the 400 m and 2.5 min walks. In women, independent of peak torque, RTD was only a significant independent correlate of the 6 m fast walk ($P < 0.001$).

Conclusions RTD independently contributes to physical functions in men but less in women. The mechanisms underlying the sex difference are unclear and require further study.

Keywords Aging; Muscle contraction; Muscle strength; Dynamometry; Walking; Physical performance; Sex difference

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Introduction

With aging, the ability to generate muscle force decreases in magnitude and speed, leading to problems with walking and balance, and ultimately, to an increased risk of disability.[1–3] Muscle force is frequently assessed as peak torque during isometric, isokinetic, or isotonic muscle contractions; these assessments do not account for speed of contraction. While peak torque is a strong predictor of physical functions,[4,5] the speed of force development may contribute independently to performance, especially in tasks that require rapid force development, such as brisk walking or jumping. One way to account for speed is to assess muscle power, an average measure of force and velocity of movement in tasks conducted at rapid speed. In cross-sectional studies, leg muscle power is superior to pure measures of strength in predicting mobility performance.[2,6] However, assessing muscle power requires special equipment and many standard tests for measuring power, such as a vertical or long jump may be risky in older adults.[7]

Assessing the rate of torque development (RTD) represents a valid alternative to muscle power because it captures the maximal rather than average value, incorporating both force and speed of contraction. Much equipment for testing muscle strength records the time course of force development which can be used to assess the rate of doing work. RTD during isometric contraction is widely used in sports research.[8–10] In contrast to muscle power, RTD can be assessed during an isometric contraction (i.e. without external mechanical movement) so is easy and safe to perform in older adults and in a variety of settings.[11,12] Thus, RTD offers potential to inform studies of aging because it captures the speed-related, dynamic component of muscle performance in a safe and feasible manner.[13–16]

Rate of torque development is known to affect lower extremity performance in patients with stroke or cerebral palsy.[17–19] However, these studies have been small and do not address aging in general. Additionally, because it is likely that age, sex, and peak torque contribute to both RTD and lower extremity performance,[5,15,20,21] the contribution of RTD to physical performance should be evaluated after adjusting for these potential confounders.

Our aim is to investigate whether, after adjusting for relevant confounders and isometric or isokinetic knee extension peak torque, RTD assessed during a test of knee extensor isometric strength is independently associated with measures of lower extremity performance. Addressing this hypothesis is important to better clarify whether RTD can be useful as a diagnostic tool or as a parameter for tracking the effectiveness of interventions such as those aimed at improving physical function in older persons.

Methods

Participants

The Baltimore Longitudinal Study of Aging (BLSA) is a prospective observational cohort study designed to investigate the aging process and to identify mechanisms underlying the decline of physical and cognitive function that occur with aging in humans.[22] Between April 2003 and February 2011, 1089 BLSA participants (49% women; 26–96 years old) performed isometric knee extension strength. The BLSA study began measuring physical performance between January 2006 and July 2007 (see legend in Table 1). During one 3 day visit, participants undergo a variety of tests, including strength and body composition. We used data from the most recent visit with data on isometric knee extension strength. The BLSA protocol was approved by the Institutional Review Board of record at the time of data collection (MedStar Health Research Institute, Baltimore, MD or National Institute of Environmental Health Sciences, NC), and written informed consent was obtained from all participants.

Table 1 Participant characteristics

	Men				Women			
	Mean	±	SD	*n*	Mean	±	SD	*n*
Age (years)	68.4	±	14.4	548	64.0	±	13.8	541
Race (black, %)	24.3			548	34.6			541
Body height (cm)	175.5	±	7.4	548	162.8	±	6.2	541
Body weight (kg)	84.5	±	14.7	548	71.0	±	14.6	541
Whole body fat mass (kg)[a]	25.5	±	9.6	520	28.8	±	10.6	516
ALM (kg)[a]	25.1	±	3.9	520	17.0	±	3.3	516
400 m walk (s)	258.8	±	60.4	315	272.4	±	54.9	270
2.5 min walk (m)	186.1	±	30.1	312	182.9	±	30.0	259
6 m fast (m/s)	1.80	±	0.46	405	1.70	±	0.35	385
6 m usual (m/s)	1.12	±	0.27	409	1.14	±	0.25	386
HABCPPB (/4 points)	2.78	±	0.73	398	2.87	±	0.63	382
CS5pace (times/s)	0.49	±	0.20	406	0.50	±	0.17	388
CS10pace (times/s)	0.46	±	0.18	405	0.46	±	0.15	385
SPPB (0–12 points)	11.1	±	1.9	395	11.3	±	1.6	385
Isometric peak torque (Nm)[b]	171.1	±	56.9	548	117.9	±	37.3	541
Concentric, isokinetic peak torque at 30 deg/s (Nm)	148.7	±	55.5	460	102.2	±	35.2	472
Peak RTD (Nm/s)[b]	886.1	±	476.2	548	511.8	±	285.4	541

ALM, appendicular lean mass; CS5pace, the timed chair stands per second for five stands; CS10pace, the timed chair stands per second for 10 stands; HABCPPB, health ABC physical performance battery; RTD, rate of torque development; SD, standard deviation; SPPB, short physical performance battery; 2.5 min walk, the distance covered by 2.5 min walk at usual pace; 400 m walk, time to complete 400 m walk at fast pace; 6 m fast, gait speed at fast pace in 6 m; 6 m usual, gait speed at usual pace in 6 m.
[a]measured by dual energy X-ray absorptiometry.
[b]measured by using an isokinetic dynamometer.
Assessment of 400 m walk started from April 2007. The 2.5 min walk started from July 2007. The 6 m gait tests, SPPB, and CS tests started from January 2006. HABCPPB started from January 2006.

Knee extension peak torques and rate of torque development assessments

Participants performed three trials of isometric knee extension at a knee angle of 120 deg with 15 s breaks between trials using a Kin-Com® isokinetic dynamometer (Kin-Com model 125E, version 3.2, Chattanooga Group, Chattanooga, TN).[23,24] In the isometric test, participants were asked to extend their knee as hard as possible for 3 s with an instructor's verbal encouragement.[25,26]

All signals were sampled at 100 Hz. After exporting the raw data, torque time trajectories were smoothed with a 5-point moving average (50 ms epochs). The percent change compared with each previous time point was calculated, and the onset of force production was defined as the time point at which the percent change $\geq$3.0%, and time after force onset was divided into 50 ms epochs (i.e. 0–50, 50–100, 100–150, …, 2950–3000 ms). Then, RTD was calculated as the slope of the torque–time relationship (Δtorque/0.05 s) within each epoch. Finally, peak RTD was defined as the highest value across epochs. We excluded trials that lacked a period of no change in torque $>$1 Nm for at least 100 ms prior to the force onset. For each trial in which RTD was calculated, isometric peak torque was defined as the peak value during that trial. We selected the trial with the highest peak torque from either leg for both RTD and isometric peak torque.

In addition, participants performed three sets of isokinetic concentric knee extension at 30 deg/s using the Kin-Com, with 15 s rest periods between trials. Concentric, isokinetic peak torque was defined as the highest value of torque from the same leg as the isometric test.

Lower extremity performance

Lower extremity performance was assessed in several ways. Gait speed was defined as distance divided by time to the tenth of a second. The 6 m walk at usual pace test (6 m usual) was performed before the 6 m walk at fast pace test (6 m fast). Participants stood with their toes just touching the start line, with 'Ready? Go', they walked from the tape line at the start to the one at the end of the course. The tests used a stopwatch to capture the time between the first footfall over the start line and the first footfall across or touching the finish line. We also collected data on a 400 m walk at fast pace (400 m, s), distance covered in a 2.5 min walk at normal pace (2.5 min, metre).[27,28] For these two tests, a 20 m walking course was set with two fluorescent orange traffic cones at each end and tape marking each metre between the cones. The examiner used a stopwatch to measure the total time to complete in 400 m walk. In 400 m walk, the examiner stopped timing when the first footfall crossed the finish line. For the 2.5 min walk, the examiner counted the number of laps and metre mark on the floor. Time started at the participants first footfall over the starting line. Standard encouragement was offered after each lap.

For the timed chair stands, participants were asked to stand all the way up and sit all the way down 10 times as quickly as possible while keeping their arms folded across their chests. We used a straight back, flat, level, firm seat 45 cm in height. The times to complete 5 and 10 stands (CS5pace and CS10pace, respectively, times per second) were recorded using a stopwatch. The examiner started timing as soon as saying 'Go' and stopped after 10 chair stands were completed. Time to complete five stands was recorded using the split button on the stopwatch. Global lower extremity performance was measured by the Short Physical Performance Battery (SPPB)[29] and the Health ABC Physical Performance Battery (HABC PPB) tests.[27] SPPB is composed of three standing balance tasks, 6m walking speed at usual pace, and a 5-time chair stand test. Results are converted to a score ranging from 0 (worst) to 12 (best) points based on predefined cut-off thresholds in each test. HABC PPB is an extended version of the SPPB aimed at minimizing a ceiling effect by increasing the number of chair stands and including more difficult balance tasks. The score of HABC PPB ranges from 0 (worst) to 4 (best).

Most participants completed the test in about 20 min including instructions and examiner demonstration. Participants could rest between tests as desired.

Body composition

A whole-body dual-energy X-ray absorptiometry (Prodigy Dual Photon X-ray Absorptiometry unit, General Electric, Milwaukee, WI) with DICOM software ver. 10.51.006 with the array mode was performed to obtain measures of whole body fat mass and appendicular lean mass (ALM) (sum of arm and leg lean mass) as previously described.[26]

Statistical analysis

Descriptive data are presented as the mean ± standard deviation or percentages. Normality and equal assumptions were verified using the Kolmogorov–Smirnov and Levene tests, respectively. Differences according to sex were assessed with unpaired *t*-test for continuous variables and chi-square tests for categorical variables. Peak RTD was log-transformed due to skewness. However, untransformed data were used in analyses that explored age-related differences.

First, we used a non-parametric strategy to explore the relationship between age and various measures of muscle strength, using locally weighted regression smoothers, LOWESS using the SAS PROC LOESS.[4] Second, to test for non-linearity of the relationship between age and these measures, we fitted quadratic regression models. Third, in only the relationships where the quadratic term significantly increased model fit, we performed piecewise regression with the Marquardt method to test the hypothesis that, on average, decline over time of these strength measures becomes steeper after a certain age. The critical age for slope change was identified using PROC NLIN in SAS, and the 95% confidential interval was calculated by using bootstrap method (resample = 2000).

Sex-specific generalized linear regression models were used to assess the cross- sectional associations of RTD or isometric peak torque with each lower extremity performance. In Model 1, we examined the associations between RTD with each lower extremity performance after adjusting for age, race (blacks vs. other races), and body mass index (BMI, kg/m^2). In Model 2, we examined the associations between isometric peak torque and each lower extremity performance after adjusting for the same variables in Model 1. Model 3 included both RTD and isometric peak torque and all potential confounders in Model 1. Model 4 further adjusted for ALM and whole body fat mass and all variables from Model 3.

We also examined the cross-sectional associations of RTD or isokinetic peak torque with each lower extremity performance by using the same sequence of analyses reported earlier.

Based on the initial exploratory analyses, we assumed that both muscle strength measures and lower extremity performance would decline and be related, predominantly later in life. Thus, we performed sensitivity analyses for the subgroup based on the age breakpoints identified earlier, to determine if the primary findings using the total study population were robust.

Statistical Analysis Software (SAS) version 9.4 for Windows (SAS Institute, Inc., Cary, NC) was used for all data processing and statistical analyses. The level of statistical significance was set as $P < 0.05$ (two-sided).

Results

The characteristics of the study population are presented in Table 1. Compared with female participants, male participants were older and had greater strength in all strength measures, as well as better physical performance. The relationship between age and measures of peak RTD, isometric peak torque, or isokinetic peak torque in men and women are depicted in Figures 1 and S2.

In men, peak RTD declined significantly with age ($\beta_{age} = -15.9$, $P < 0.0001$, $R^2 = 0.23$). The decline was linear, as indicated by the lack of improvement in fit when a quadratic term for age was included in the model ($\beta_{age2} = 0.05$, $P = 0.48$, $R^2 = 0.23$). Isometric peak torque also declined with age ($\beta_{age} = -2.3$, $P < 0.0001$, $R^2 = 0.33$), but the introduction of a quadratic term for age significantly improved the fit of the model ($\beta_{age2} = -0.02$, $P = 0.02$, $R^2 = 0.34$), with a steeper decline after the age of 63.0 [95% confidence interval, CI 51.2–74.8] (see Supporting Information, Figure S2a). Isokinetic peak torque also declined with age ($\beta_{age} = -2.1$, $P < 0.0001$, $R^2 = 0.31$). The relationship was non-linear ($\beta_{age2} = -0.03$, $P = 0.006$, $R^2 = 0.32$), with significantly steeper decline after the age of 63.0 years [95% CI: 51.9–74.0] (see Supporting Information, Figure S3).

In women, peak RTD, isometric peak torque, and isokinetic peak torque declined with age (RTD, $\beta_{age} = -8.0$, $P < 0.0001$, $R^2 = 0.15$; isometric peak torque, $\beta_{age} = -1.3$, $P < 0.0001$, $R^2 = 0.22$; isokinetic peak torque, $\beta_{age} = -1.2$, $P < 0.0001$, $R^2 = 0.22$), and all declines were non-linear (RTD, $\beta_{age2} = -0.2$, $P < 0.0001$, $R^2 = 0.18$; isometric peak torque, $\beta_{age2} = -0.03$, $P < 0.001$, $R^2 = 0.26$; isokinetic peak torque, $\beta_{age2} = -0.03$, $P < 0.0001$, $R^2 = 0.26$), with accelerated decline after 55.1 years [95% CI: 48.9–62.1] for RTD, 61.9 years [95% CI: 55.0–67.7] for isometric peak torque, and after 61.0 years [95% CI: 54.0–68.0] for isokinetic peak torque (Figure 1 and see Supporting Information, Figures S2b and S3b). Based on these analyses, we created a subgroup of older participants assuming that declines in strength and function accelerate, on average after the age of 60.

Next, we examined relationships between RTD and isometric peak torque with lower extremity performance (Tables 2a

Figure 1 Relationship between age and peak rate of torque development. In men, the solid line is a locally weighted regression smoother with 95% confidence interval. In women, the solid line is a piecewise regression with a breakpoint estimated at 55.1 (48.9–62.1) years old.

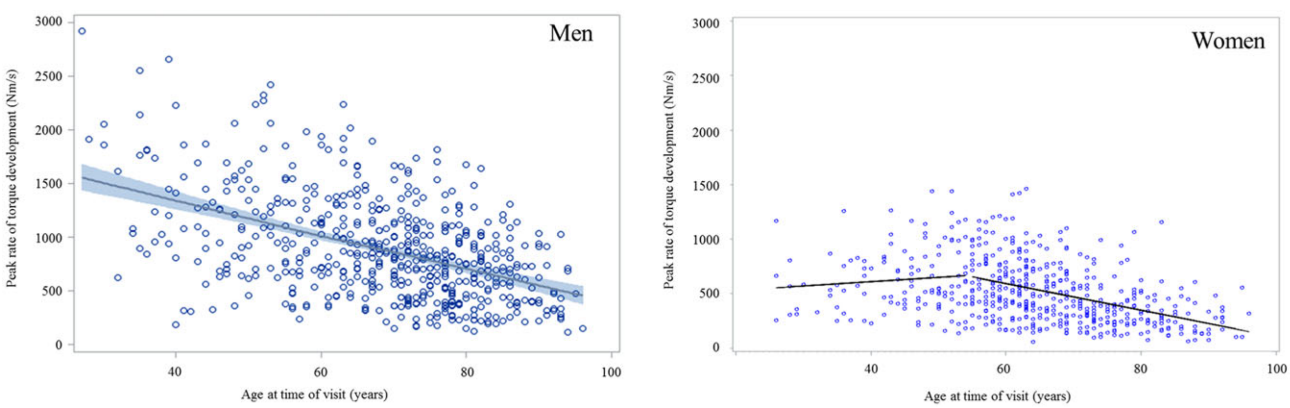

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Table 2a The relationship of rate of torque development or isometric knee extension peak torque with physical performance tests in men

	Men																	
	Model 1			Model 2			Model 3						Model 4					
	RTD[a]			ISOM			RTD[a]		ISOM				RTD[a]		ISOM			
	β	P value	R^2	β	P value	R^2	β	P value	β	P value	R^2		β	P value	β	P value	R^2	
400 m walk (s) (n = 311)	−0.17	0.001	0.44	−0.23	<0.0001	0.46	−0.07	0.21	−0.18	0.003	0.46		−0.07	0.18	−0.14	0.03	0.47	
2.5 min walk (m) (n = 308)	0.15	0.01	0.26	0.17	0.01	0.26	0.09	0.19	0.11	0.14	0.26		0.09	0.19	0.07	0.35	0.27	
6 m fast (m/s) (n = 396)	0.24	<0.0001	0.40	0.29	<0.0001	0.41	0.14	0.01	0.20	0.001	0.42		0.14	0.01	0.20	0.002	0.42	
6 m usual (m/s) (n = 399)	0.22	<0.0001	0.29	0.22	<0.0001	0.28	0.16	0.01	0.11	0.08	0.30		0.16	0.01	0.10	0.17	0.30	
HABCPPB (n = 390)	0.23	<0.0001	0.39	0.23	<0.0001	0.38	0.17	0.002	0.11	0.08	0.39		0.17	0.002	0.12	0.06	0.40	
CS5pace (times/s) (n = 396)	0.18	0.0002	0.23	0.19	0.001	0.22	0.13	0.04	0.10	0.14	0.23		0.12	0.04	0.15	0.03	0.30	
CS10pace (times/s) (n = 395)	0.20	<0.0001	0.23	0.23	<0.0001	0.23	0.13	0.04	0.14	0.04	0.24		0.12	0.04	0.19	0.01	0.30	
SPPB (n = 387)	0.28	<0.0001	0.24	0.24	<0.0001	0.21	0.23	0.0002	0.08	0.23	0.24		0.23	0.0002	0.08	0.30	0.25	

CS5pace, chair stands per second for five stands; CS10pace, chair stands per second for 10 stands; HABCPPB, health ABC physical performance battery; ISOM, peak torque (Nm) measured by isometric knee extension strength at 120 deg; RTD, rate of torque development; SPPB, short physical performance battery; 2.5 min walk, the distance covered by 2.5 min walk at usual pace; 400 m walk, time to complete 400 m walk at fast pace; 6 m fast, gait speed at fast pace in 6 m; 6 m usual, gait speed at usual pace in 6 m.
[a]log transformed. All models, $P < 0.0001$.
Values are standardized regression coefficient from generalized linear regression models. In each physical performance test, Models 1 and 2 were adjusted for age, race, and body mass index. Model 3 was adjusted for variables in Model 1 + ISOM. Model 4 was adjusted for variables in Model 3 + appendicular lean mass and whole body fat free mass.

Table 2b The relationship of rate of torque development or isometric knee extension peak torque with physical function tests in women

	Women															
	Model 1			Model 2			Model 3					Model 4				
	RTD[a]			ISOM			RTD[a]		ISOM			RTD[a]		ISOM		
	β	P value	R^2	β	P value	R^2	β	P value	β	P value	R^2	β	P value	β	P value	R^2
400 m walk (s) (n = 260)	−0.20	<0.0001	0.51	−0.30	<0.0001	0.54	−0.05	0.39	−0.27	<0.0001	0.54	−0.06	0.33	−0.23	0.001	0.54
2.5 min walk (m) (n = 252)	0.16	0.01	0.29	0.21	0.001	0.30	0.07	0.34	0.16	0.048	0.30	0.07	0.37	0.15	0.08	0.30
6 m fast (m/s) (n = 375)	0.22	<0.0001	0.48	0.25	<0.0001	0.48	0.12	0.01	0.16	0.003	0.49	0.13	0.01	0.13	0.03	0.50
6 m usual (m/s) (n = 376)	0.13	0.01	0.29	0.13	0.01	0.29	0.08	0.16	0.08	0.22	0.29	0.09	0.13	0.05	0.47	0.30
HABCPPB (n = 372)	0.12	0.01	0.35	0.14	0.01	0.35	0.07	0.20	0.09	0.16	0.36	0.07	0.24	0.11	0.09	0.36
Chair stand test (times/s)																
CS5pace (times/s) (n = 378)	0.10	0.047	0.20	0.13	0.02	0.20	0.04	0.49	0.10	0.15	0.20	0.02	0.69	0.18	0.01	0.27
CS10pace (times/s) (n = 375)	0.11	0.03	0.25	0.17	0.002	0.26	0.03	0.68	0.15	0.02	0.26	0.00	0.97	0.25	0.0003	0.33
SPPB (n = 375)	0.09	0.09	0.18	0.10	0.08	0.18	0.05	0.42	0.06	0.38	0.19	0.04	0.51	0.10	0.19	0.20

CS5pace, chair stands per second for five stands; CS10pace, chair stands per second for 10 stands; HABCPPB, health ABC physical performance battery; ISOM, peak torque (Nm) measured by isometric knee extension strength at 120 deg; RTD, rate of torque development; SPPB, short physical performance battery; 2.5 min walk, the distance covered by 2.5 min walk at usual pace; 400 m walk, time to complete 400 m walk at fast pace; 6 m fast, gait speed at fast pace in 6 m; 6 m usual, gait speed at usual pace in 6 m.
[a]log transformed. All models, $P < 0.0001$.
Values are standardized regression coefficient from generalized linear regression models. In each physical performance test, Models 1 and 2 were adjusted for age, race, and body mass index. Model 3 was adjusted for variables in Model 1 + ISOM. Model 4 was adjusted for variables in Model 3 + appendicular lean mass and whole body fat free mass.

Table 3a The relationship of rate of torque development or concentric, isokinetic knee extension at 30 deg/sec with physical function tests in men

	Men																	
	Model 1			Model 2			Model 3						Model 4					
	RTD[a]			ISOK			RTD[a]		ISOK				RTD[a]		ISOK			
	β	*P* value	R^2	β	*P* value	R^2	β	*P* value	β	*P* value	R^2		β	*P* value	β	*P* value	R^2	
400 m walk (sec) (*n* = 234)	−0.14	0.01	0.46	−0.19	0.001	0.47	−0.05	0.39	−0.16	0.02	0.48		−0.06	0.35	−0.12	0.11	0.48	
2.5 min walk (m) (*n* = 226)	0.14	0.03	0.22	0.14	0.06	0.22	0.11	0.19	0.07	0.42	0.22		0.11	0.19	0.03	0.72	0.23	
6 m fast (m/s) (*n* = 314)	0.24	<0.0001	0.38	0.28	<0.0001	0.38	0.14	0.02	0.19	0.01	0.39		0.14	0.02	0.18	0.01	0.39	
6 m usual (m/s) (*n* = 317)	0.22	<0.0001	0.29	0.19	0.002	0.27	0.19	0.005	0.07	0.35	0.29		0.18	0.01	0.05	0.50	0.30	
HABCPPB (*n* = 308)	0.22	<0.0001	0.38	0.15	0.01	0.35	0.22	0.001	0.01	0.91	0.38		0.21	0.001	0.03	0.68	0.39	
CS5pace (times/s) (*n* = 314)	0.17	0.003	0.22	0.11	0.08	0.20	0.17	0.01	0.00	1.00	0.22		0.15	0.02	0.07	0.36	0.28	
CS10pace (times/s) (*n* = 314)	0.20	0.001	0.22	0.17	0.01	0.21	0.16	0.02	0.07	0.38	0.22		0.14	0.03	0.14	0.08	0.28	
SPPB (*n* = 305)	0.26	<0.0001	0.23	0.18	0.004	0.20	0.24	0.001	0.03	0.68	0.23		0.24	0.001	0.04	0.63	0.24	

CS5pace, chair stands per second for five stands; CS10pace, chair stands per second for 10 stands; HABCPPB, health ABC physical performance battery; ISOK, peak torque (Nm) measured by concentric, isokinetic knee extension strength at 30 deg/s; RTD, rate of torque development; SPPB, short physical performance battery; 2.5 min walk, the distance covered by 2.5 min walk at usual pace; 400 m walk, time to complete 400 m walk at fast pace; 6 m fast, gait speed at fast pace in 6 m; 6 m usual, gait speed at usual pace in 6 m.
[a]log transformed. All models, $P < 0.0001$.
Values are standardized regression coefficient from generalized linear regression models. In each physical performance test, Model 1 and 2 were adjusted for age, race, and body mass index. Model 3 was adjusted for variables in Model 1 + ISOK; Model 4 was adjusted for variables in Model 3 + appendicular lean mass and whole body fat free mass.

Table 3b The relationship of rate of torque development or concentric, isokinetic knee extension peak torque at 30 deg/sec with physical function tests in women

	Women															
	Model 1			Model 2			Model 3					Model 4				
	RTD[a]			ISOK			RTD[a]		ISOK			RTD[a]		ISOK		
	β	*P* value	R^2	β	*P* value	R^2	β	*P* value	β	*P* value	R^2	β	*P* value	β	*P* value	R^2
400 m walk (s) (*n* = 201)	−0.18	0.001	0.53	−0.32	<.0001	0.57	−0.04	0.48	−0.29	<.0001	0.57	−0.05	0.44	−0.27	0.0004	0.57
2.5 min walk (m) (*n* = 191)	0.14	0.03	0.34	0.24	0.001	0.36	0.04	0.65	0.21	0.02	0.36	0.04	0.66	0.21	0.03	0.36
6 m fast (m/s) (*n* = 309)	0.19	<.0001	0.48	0.16	0.001	0.47	0.16	0.004	0.07	0.26	0.48	0.17	0.002	0.01	0.88	0.49
6 m usual (m/s) (*n* = 310)	0.10	0.048	0.31	0.05	0.38	0.31	0.11	0.07	−0.02	0.78	0.32	0.12	0.05	−0.06	0.45	0.32
HABCPPB (*n* = 306)	0.11	0.03	0.37	0.14	0.01	0.37	0.06	0.32	0.10	0.14	0.37	0.06	0.34	0.11	0.13	0.37
CS5pace (times/s) (*n* = 312)	0.08	0.15	0.24	0.11	0.08	0.24	0.04	0.57	0.08	0.25	0.24	0.03	0.67	0.16	0.04	0.30
CS10pace (times/s) (*n* = 309)	0.08	0.12	0.26	0.15	0.01	0.27	0.02	0.81	0.14	0.05	0.27	0.00	0.96	0.22	0.003	0.34
SPPB (*n* = 309)	0.08	0.18	0.20	0.11	0.07	0.20	0.03	0.69	0.10	0.19	0.20	0.02	0.76	0.13	0.11	0.21

CS5pace, chair stands per second for five stands; CS10pace, chair stands per second for 10 stands; HABCPPB, health ABC physical performance battery; ISOK, peak torque (Nm) measured by concentric, isokinetic knee extension strength at 30 deg/s; RTD, rate of torque development; SPPB, short physical performance battery; 2.5 min walk, the distance covered by 2.5 min walk at usual pace; 400 m walk, time to complete 400 m walk at fast pace; 6 m fast, gait speed at fast pace in 6 m; 6 m usual, gait speed at usual pace in 6 m.
[a]log transformed. All models, $P < 0.0001$.
Values are standardized regression coefficient from generalized linear regression models. In each physical performance test, Model 1 and 2 were adjusted for age, race, and body mass index. Model 3 was adjusted for variables in Model 1 + ISOK; Model 4 was adjusted for variables in Model 3 + appendicular lean mass and whole body fat free mass.

and 2b), separately in men and women, using multivariate linear regression models adjusting for age, race, and BMI. When examined separately, isometric peak torque and RTD were significantly associated with all lower extremity performance measures. When RTD and isometric peak torque were included in the same model, results differed by sex (Tables 2 and 3 and Model 3). In men, RTD remained a significant independent predictor of all lower extremity performance measures, except the 400 m (P = 0.21) and the 2.5 min (P = 0.19) walks. After further adjusting for ALM and fat mass, results were substantially unchanged (Model 4). However, in women, when RTD and isometric peak torque were included in the same model, RTD was no longer a significant correlate of most lower extremity performance tests, except the 6 m fast walk (P = 0.01) (Model 3). In the same models, isometric peak torque was a significant independent correlate of performance in the 400 m walk, the 6 m fast walk, and chair stand tests. These findings were substantially unchanged after adjusting for body composition (Model 4).

We then examined relationships between RTD and isokinetic peak torque with lower extremity performance using similar multivariate linear regression models (Tables 3a and 3b). Similar to the results using isometric peak torque, in men, RTD was significantly correlated with all tests of lower extremity performance except the 400 m walk (P = 0.39) and the 2.5 min walk (P = 0.19). Again, in women, RTD was significantly associated with the 6 m fast speed but not with any other lower extremity performance test.

In sensitivity analyses limited to participants 60 years and older, findings were substantially similar to those that included all participants. Two exceptions were noted. In men older than 60 years, RTD was no longer significantly associated with the chair stand tests. In women, the relationship between RTD and the 6 m fast was no longer significant. (See Supporting Information, Tables S4a and b and S5a)

Discussion

In men, rate of force development, independent of isometric or isokinetic peak torque, is significantly associated with most measures of physical performance, except those that are designed to especially reflect endurance. Surprisingly, in women, RTD was independently correlated with the 6 m fast walk, but not with any other performance test. RTD and peak torque appear to contribute differently by sex to physical performance.

These findings vary in part from prior work, potentially due to differences in populations, how RTD is calculated, or types of performance measures. In a small study of older adults aged 65–80, (38.1% male; n = 21), Altubasi found that knee extension RTD assessed as time from onset to peak torque, rather than by 50 ms epoch, was moderately correlated with stair climbing (r = −0.57) but not with the timed up and go, ramp up, or 4 m walk with usual pace tests.[30] In patients affected by multiple sclerosis (26% male; n = 35), Kjolhede *et al*. failed to demonstrate an independent effect of peak RTD adjusted for body weight on a usual pace 2 min walk after accounting for concentric, isokinetic knee extensor peak torque.[31]

Why would RTD mostly affect performance on shorter rather than longer tasks? In another study of older adults assessing task-dependent associations among muscle strength, muscle contraction velocity, and physical function,[32] muscle contraction velocity was found to be more important than muscle strength for walking tasks but less important for SPPB.[32] In our study, physical performance tests significantly associated with peak RTD did not necessarily represent tasks that require maximum muscle contraction, endurance, or rapid force development. In other words, the contribution of peak RTD to performance seems to be more relevant during short quick movements. Longer activities such as long distance walks require prolonged muscle action and endurance, which depend heavily on the capacity to generate energy over time. The differential relationship of RTD with performance based on energy requirements should be assessed in future studies.

We found important differences in the relationship between RTD and performance by sex. Sex differences in RTD have been reported. In one study, compared with women, men had greater knee extension RTD at 250 ms from force onset.[15] Another study, assessing RTD at 150 ms from onset, also reported higher knee extension RTD in men compared with women and suggested that the sex difference might be attribute to muscle size.[20] Indeed, various measures of body composition and muscle strength are known to differ by sex and have been reported to predict mobility function better in men than women.[33–36] Because over the life span, women consistently have lower muscle strength and mass relative to body weight, women may use different strategies to move, relying less on pure strength and more on coordination and timing of synergies among muscle groups. Menopause may also play a role in sex differences. As shown in Figure 1, while RTD in men declines linearly with age, in women, RTD starts declining more rapidly around the age of menopause. In animal studies, oestrogen affects the contractile properties of contractile proteins and skeletal muscle, leading to changes in force development.[37,38] Furthermore, there are sex differences in rates of conditions that might alter the effect of strength on performance. Women have higher rates of osteoarthritis and osteoporosis than men, perhaps reducing the influence of strength on mobility performance.[39] Other factors that differ by sex include rates of physical activity and the proportion of body weight accounted for by fat, which may affect the capacity to generate muscle power, also resulting in a need to use alternative strategies to move successfully.[40] Ultimately, these important sex differences in effects on physical performance should be tested in future studies. The alternative strategies used by women should be explicated. These sex differences could inform how exercise interventions might be tailored to different needs by sex.

Rate of torque development is not yet a standardized test and lacks a protocol that specifies joint angles, verbal instructions, or how to define and use time periods. As a result, absolute RTD values, even when age and sex are similar, vary across the literature. For example, in one study, at a 90 deg knee joint angle, maximum RTD among men in their 40s was 801 Nm/s, while it was 601 Nm/s for men in their 60s.[41] In another study at a 120 deg knee joint angle, peak RTD in middle-aged men (50.6 years) was 1744 Nm/s, while it was 1215 Nm/s in men with an average age in the late 60s.[42] The knee joint angle in our study is also 120 deg, but our peak RTD values are lower. One potential difference is the specific verbal instructions used. We asked participants 'to push as hard as possible'. Higher RTD may be achieved by using the instruction 'as fast as possible'.[43] These variations in how to measure RTD might affect results of tests of associations between RTD and physical performance. Consistent standardization of RTD could provide a way to compare relationships across studies.

Our study has important strengths. Our sample size is large, with a broad distribution of age, sex, and race. To determine independent associations between RTD and performance, we accounted for measures of peak torque and other confounders. We performed a sensitivity analysis to determine how associations might differ in a sample limited to those over age 60. Our study also has limitations. Not all participants completed all the performance tests; 11% did not complete the 400 m walk test due to health status or other problems.[28] It is possible that informative censoring might explain the lack of association between RTD and some of the long walks. This initial study is limited to cross-sectional associations. Although the BLSA assesses multiple aspects of performance, the ability to generate ballistic movements is not assessed. Because in physically active young men, knee extensor RTD is known to correlate with ballistic movements such as 10 m sprint performance ($r = -0.66$) and jump performance ($r = 0.68$),[44,45] RTD in our study might have shown associations with tasks that are more dependent on ballistic motion.

We find that, in men, RTD contributes to physical performance independent of peak torque, whether assessed by isokinetic or isometric dynamometry. The role of RTD appears to be stronger in men than women, but the mechanisms underlying this discrepancy remain unclear. Longitudinal studies of both sexes and a broad age range should include standardized measures of RTD, a broader array of performance measures and indicators of other factors that affect performance, especially those related to motor control.

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Online supplementary material

Additional Supporting Information may be found online in the supporting information tab for this article.

Table S4a. Relationship of rate of torque development or isometric knee extension peak torque with physical function tests in men over 60 years old

Table S4b. Relationships of rate of torque development or isometric knee extension peak torque with physical function tests in women over 60 years old

Table S5a. Relationships of rate of torque development or concentric, isokinetic peak torque at 30 deg/s with physical function tests in men over 60 years old

Fig. S2. Relationship between age and peak torque in isometric knee extension at 120 deg. In men, the solid line is a piecewise regression with a breakpoint estimated at 63.0 [51.2-74.8] years old. In women, the solid line is a piecewise regression with a breakpoint estimated at 61.9 [55.0-67.7] years old.

Fig. S3. The relationship between age and peak torque in concentric, isokinetic knee extension at 30 deg/s. In men, the solid line is a piecewise regression with a breakpoint estimated at 63.0 [51.9-74.0] years old. In women, the solid line is a piecewise regression with a breakpoint estimated at 61.0 [54.0-68.0] years old.

Conflict of interest

Yusuke Osawa, Stephanie A. Studenski, and Luigi Ferrucci declare no conflicts of interest.

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