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The specific contributions of force and velocity to muscle power in older adults

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Abstract

The purpose of this study is to examine the relative importance of the force-based and velocity-based measures of muscle performance to explain inter-individual differences in power production capability and functional task performance. Participants included seventy-nine men and women: middle-aged healthy adults (MH: 40–55 years), older healthy adults (OH: 70–85 years), and older adults with mobility limitations (OML: 70–85 years). Muscle power at 180°/s, isometric maximal torque, and maximal contraction velocity at 40% 1RM were measured during unilateral leg extension. The Short Physical Performance Battery (SPPB) was used to differentiate between healthy and mobility limited older adults. Functional task performance was assessed using multiple chair rise and stair climb tests. Leg extensor force (torque), but not maximal contraction velocity, was significantly associated with muscle power in MH. Both torque and velocity were significantly associated with muscle power in OH. Maximal velocity, but not torque, was associated with power in OML. Maximal velocity demonstrated an association with multiple chair rise time and stair climb time in OML, but not MH or OH. It is concluded that movement velocity is an increasingly important determinant of maximal power output with advancing age. Furthermore, movement velocity is also a critical component of functional task performance with aging and may contribute to functional deficits. These findings help to explain why the rate-dependent variable power has emerged as a critical component of both assessment and rehabilitation of muscular performance and physical function in older adults.

Keywords

Power; Velocity; Strength; Aging; Function

1. Introduction

Muscle power is now acknowledged as a valuable measure for quantifying age-related physical impairment (Bean et al., 2010; Foldvari et al., 2000; Reid et al., 2008). Power is defined as work performed over a period of time, or as the product of force and movement velocity. Because power reflects both force production and movement velocity, altered neural or muscular capability affecting either factor will contribute to declines in power and potentially to declines in physical function. In contrast, traditional strength assessments (e.g., isometric maximal voluntary contraction (MVC) and one-repetition maximum (1RM)) may be less sensitive to altered neural or muscular capability because they are predominantly force-dependent. Indeed, power has been shown to decline earlier and more rapidly than strength with advancing age (Foldvari et al., 2000; Metter et al., 1997).

Maximizing power production capability is considered to be an important objective for maintaining physical function with aging (Bean et al., 2010; Foldvari et al., 2000; Reid et al., 2008). However, achieving this objective requires an improved understanding of the factors that limit muscle power, and how these factors may differ with age and functional status. Muscle size is undoubtedly an important factor to age-related declines in power production (Nogueira et al., 2009). Yet a growing body of evidence indicates that muscle size and strength are not as closely linked as previously assumed (Clark and Manini, 2008). Accordingly, there is now increased interest in understanding the determinants of muscle performance rather than just muscle size. A number of recent studies report considerable impairment of movement velocity with aging. For instance, isometric force production is less impaired than dynamic force production in the lower extremities of healthy older adults (Clark et al., 2010; Dalton et al., 2010). Moreover, maximal contraction velocity under unloaded or isotonic resistance conditions is considerably slowed with aging (Dalton et al., 2010; Lanza et al., 2003) and may be a key component in the onset of functional difficulties in the elderly (Van Roie et al., 2011). Further investigation into the relative importance of force and velocity to power production is an important step toward understanding the mechanisms limiting power production capability in older adults.

The purpose of this study is to examine the relative importance of force-based and velocity-based measures of muscle performance to explain inter-individual differences in power production capability and functional task performance. Three distinct cohorts were assessed: healthy middle-aged adults, healthy older adults, and older adults with mobility limitations. We hypothesized that the velocity-based measure would be more important to muscle power and functional task performance in the older groups than in the middle-aged group, and particularly in the group with mobility limitations.

2. Methods

2.1. Participants

Data were collected from 79 participants: 25 healthy middle-aged adults (mean age 47.2 ± 4.5 years), 28 healthy older adults (mean age 73.6 ± 3.5 years), and 26 older adults with mobility limitations (mean age 77.9 ± 4.3 years). All procedures were approved by the Tufts University Health Science Campus Institutional Review Board and all subjects provided their written informed consent prior to participation.

Volunteers were recruited by local newspaper advertisements, direct mailing to volunteers from earlier studies at our center, and posting of flyers. Three specific groups were recruited: middle-aged healthy adults (MH, age 40–55 years), older healthy adults (OH, age 70–85 years), and older adults with mobility limitations (OML, age 70–85 years). Volunteers were screened by telephone using the following exclusion criteria: presence of

unstable chronic disease, acute or terminal illness, myocardial infarction within 6 months (or other symptomatic coronary artery disease), uncontrolled hypertension ($>150/90$ mm Hg), fracture in the previous 6 months, diseases or medications affecting neuromuscular function, anticoagulation therapy (due to a muscle biopsy procedure, data not presented here), hormone replacement therapy, body mass index less than 19 kg/m^2 or greater than 33 kg/m^2 , weight loss or gain within the previous 6 months, and participation in a strength or endurance training program within the previous 6 months. Volunteers being considered for MH and OH were also required to not be taking any prescription medications. Individuals who passed the telephone screening were further screened by a licensed physician or nurse practitioner, including assessment of the presence of lower extremity joint pain and administration of the Folstein Mini-Mental State Examination (MMSE) (Folstein et al., 1975) and Short Physical Performance Battery test (SPPB) (Guralnik et al., 1994). Persons with MMSE score less than 23 or with joint pain were excluded. The SPPB, which probes the domains of strength, ambulation capacity, and balance, is predictive of future disability (Guralnik et al., 1994) and was used to classify the older adults into the OH and OML groups. Older adults scoring 9 or less (out of a possible 12 points) were classified as OML, whereas those scoring greater than 9 and who were not taking prescription medication were classified as OH.

2.2. Protocol

Maximal voluntary knee extensions were performed on an iso-kinetic dynamometer (Cybex II Isokinetic Dynamometer, Cybex Division of Lumex Inc, Ronkonkama, NY) and on a pneumatic resistance training machine (Keiser A420 Model Keiser Corp, Fresno, CA). Participants were seated upright with the hip and knee of the dominant leg flexed to approximately 85° and 90° , respectively. The testing apparatus was adjusted such that the lateral epicondyle of the dominant knee was aligned with the equipment's axis of rotation. The limb was secured to the equipment's lever arm by a padded strap placed 1 in. above the ankle.

2.3. 1RM and velocity

Each participant's one repetition maximum (1RM), defined as the greatest load that could be moved one time through the full range of motion using proper technique (Callahan et al., 2007) was measured on the pneumatic leg press. Prior to testing, each subject was asked to hold the dominant leg in full extension against minimal resistance while the examiner recorded the limb position using real-time output provided by the manufacturer's software. 1RM attempts were considered successful if the participant reached 90% of criterion limb position. Resistance was increased after each trial unless the participant failed to achieve 90% of maximal limb position, in which case the resistance was reduced by half of the previous increment. Testing continued until the participant failed two consecutive trials at a given level of resistance. Each trial was followed by 1 min of rest and 1RM was typically attained within 6–8 trials.

To evaluate contraction velocity while controlling for individual differences in absolute strength, the resistance level of the pneumatic machine was set to 40% of the participant's 1RM. Participants were instructed to perform maximal effort knee extension as quickly and explosively as possible through the entire concentric range of motion. Five maximal effort trials were performed, with at least 30 s of rest between each trial.

2.4. Torque and power

Torque (i.e., rotational force) and power were assessed on the iso-kinetic dynamometer. To evaluate torque in isolation, isometric MVCs of the knee extensors were performed. The leg was held in 60° of knee flexion and the participant was instructed to push as hard as possible

for 3–5 s while the examiner provided strong verbal encouragement. Trials were performed until successive attempts showed improvement of <5% (generally 3–5 trials). Following measurement of MVC, the dynamometer was set to isokinetic mode at 180°/s. Participants were instructed to perform 5 consecutive maximal voluntary knee extension trials.

2.5. Functional assessments

Stair climb was assessed using a standard riser of stairs. The subject was asked to ascend a 10 rise set of stairs as fast as they could. Subjects could ascend holding the railing or using their assistive device if necessary. Repeated multiple chair rise time was determined on a standard chair with the subject holding arms across the chest. Subjects were asked to stand and sit 10 times as fast as they could. Participants performed each functional task twice, and the average was used for subsequent analysis.

2.6. Instrumentation

For the isokinetic dynamometer, torque and angular velocity signals were directly sampled at 1 kHz by a Powerlab/16SP A/D system with Chart v5.4 software (ADInstruments, Colorado Springs, CO). For the pneumatic resistance training machine, pressure and linear position were sampled from pneumatic pistons at 400 Hz and trigonometrically converted to SI units of torque and angular velocity by the manufacturer's software. All data were saved to disk for offline analysis.

Computed tomography (CT) scans of the thigh were obtained at the midpoint of the femur using a Siemens Somatom Scanner (Erlangen, Germany) operating at 120 kV and 100 mA, a slice width of 10 mm and a scanning time of 1 s. All scans were analyzed by a single blinded assessor using SliceOmatic v4.2 software (Tomovision, Montreal, Canada). Images were reconstructed on a 512×512 matrix with a 25-cm field of view, and anterior compartment muscle cross-sectional area (CSA) was measured by manual tracing using, when applicable, intermuscular adipose tissue as a guide. Muscle CSA was measured in the range of 0–100 Hounsfield units and calculated as the sum of low- and normal-density area.

2.7. Data analysis

All data were analyzed offline using Matlab 7.0 (The Mathworks, Natick, MA) and statistical analysis was performed using JMP statistical software (v. 9.0.2, SAS Institute Inc, Cary, NC). Concentric knee extension torque and velocity were averaged over a window of 70–50° of knee flexion. Power was calculated by multiplying torque by velocity (after converting from deg/s to radians/s). Isometric MVC torque was measured at 60° of knee flexion, and defined as the highest value sustained over a 250 ms window. For each testing condition the highest three values of the five trials were averaged and used for statistical analysis. Because this study is focused on muscle performance rather than muscle size, specific torque and specific power were calculated by normalizing MVC and power, respectively, to cross sectional area of the quadriceps muscle for each participant. Force-based muscle performance was indicated by specific torque (TORs) and velocity-based muscle performance was indicated by velocity at 40% 1RM (VEL).

2.8. Statistics

Within each group, multivariable least squares regression was used to determine the ability of TORs and VEL to account for the inter-individual variability in PWRs. An a priori modeling technique was utilized in order to identify the role of each specific predictor (TORs and VEL) on the outcome (PWRs). Gender has been cited as a possible confounder, and was thus included in the model (Sayers et al., 2005). The proportion of variation in PWRs accounted for by each main variable (TORs and VEL) was calculated as partial R^2

values. Colinearity between predictors was assessed by examining the variance inflation factor (VIF) of each variable.

To determine the ability of TORs and VEL and to account for the inter-individual variability of functional task performance (i.e. multiple chair rise and stair climb), a least squares multivariate regression model was constructed for all subjects and also stratified by group. This model also included gender and body weight as potential confounders of functional outcomes (Brown et al., 1995). Statistical significance was set at $p=0.05$ for all analyses.

3. Results

3.1. Participants

Data were collected for 79 participants, including 25 MH (47.2 ± 4.51 years, 11.7 ± 0.46 SPPB), 28 OH (73.67 ± 3.52 , 10.89 ± 0.91 SPPB), and 25 OML (77.9 ± 4.33 , 7.88 ± 1.24 SPPB).

3.2. Force/torque, velocity and power

Means and standard deviations of all outcomes (TORa, TORs, VEL, PWRa, and PWRs) are presented in Table 1. Results of the multivariate regression reveal that for MH subjects, TORs was highly associated with PWRs (Total Model $R^2=0.46$; TORs $p=0.005$, partial $R^2=0.30$) but VEL was not ($p=0.13$, partial $R^2=0.13$). In OH, both TORs (Total Model $R^2=0.70$; TORs $p=0.001$, partial $R^2=0.36$) and VEL ($p<0.001$, partial $R^2=0.4$) were highly associated with PWRs. However, in OML, VEL (Total Model $R^2=0.47$; VEL $p=0.005$, partial $R^2=0.13$) was significantly associated, but TORs was not ($p=0.47$, partial $R^2=0.01$) (Fig. 1). Gender was not associated with PWRs in any of the groups (Table 2). It should be noted that an outlier was removed for the regression analysis. One OML participant demonstrated an absolute power (PWRa) output of 36.3 W (compared to a mean PWRa output of 119.4 W, S.D.=50.17) and was confirmed as an outlier (Studentized Residual of -2.51 and Cook's Distance of 0.14).

Colinearity between TORs and VEL was also not significant.

3.3. Functional outcomes

VEL strongly accounted for the inter-individual variability on performance of multiple chair rise ($p<0.0001$) and stair climb performance ($p<0.0001$) when assessed across all study participants. In contrast, TORs was not associated with multiple chair rise or stair climb performance ($p=0.86$, $p=0.066$, respectively). Gender was not significantly associated with performance of either functional task.

Further analysis within each group revealed no association between VEL and multiple chair rise for MH (Total Model $R^2=0.027$, $p=0.74$,) or OH (Total Model $R^2=0.32$; $p=0.39$,) but was significantly associated with multiple chair rise performance in OML (Total Model $R^2=0.59$; $p=0.0007$). TORs, body weight and gender were not associated with multiple chair rise performance in any group (Table 3).

Analysis of the relationship between VEL and stair climb time within each group demonstrated no association in MH (Total Model $R^2=0.15$; $p=0.74$) or OH (Total Model $R^2=0.25$; $p=0.52$,), but did demonstrate a significant association within OML (Total Model $R^2=0.29$; $p=0.034$) (Table 3). TORs, body weight and gender were not associated with stair climb performance in any group (Table 3).

It should be noted that an outlier was removed for analysis of multiple chair rise. One participant demonstrated a multiple chair rise time of 83 s (compared to a mean multiple chair rise of 25.44 s, S.D.=9.69) and was confirmed as an outlier (Studentized Residual of

3.77 and Cook's Distance of 0.304). Only after removal of this outlier was there a significant association between VEL and multiple chair rise time within the OML group.

4. Discussion

This study examines the relative importance of force-based and velocity-based measures of muscle performance to explain power production capability in older adults. The results demonstrate that velocity is an increasingly influential determinant of power production capability with aging and with lower mobility function. Specifically, VEL demonstrated a stronger association than TORs to power output for OH and OML compared to MH (Table 2). This finding suggests that neural and muscular factors underlying movement velocity may be more compromised than those underlying force production (after accounting for muscle size).

A previous study has reported that force, rather than velocity, contributes more to power reductions with aging (Yamauchi et al., 2009). However, that study reported absolute torque and power in two age groups (young and elderly) while we analyzed specific torque and specific power. Absolute torque is largely dependent on muscle size, and is undoubtedly an important contributor to power production. Our decision to correct for muscle size was motivated by the objective of assessing how aspects of muscle performance other than size affect power production and functional ability.

Velocity was also shown to be an increasingly important component of functional ability with aging. VEL, rather than TORs, demonstrated a significant effect on both multiple chair rise and stair climb when examining inter-individual variability in middle aged (MH) and older adults (OH, OML). When examining those individuals in the mobility limited group (OML), VEL was the only significant variable associated with multiple chair rise time and stair climb, indicating that the velocity component of muscle performance is important to functional capability (Table 3).

Although relatively few studies have examined the components of muscle power on function, one report has suggested that contraction velocity is a stronger predictor of performance of lower intensity functional tasks than muscle strength (Sayers et al., 2005). Due to our unique approach of stratifying our older population by functional ability (SPPB score), our results may further demonstrate the importance of contraction velocity to declines in mobility function with aging. An interesting contrast with this prior study, however, is that our analysis did not demonstrate a significant effect of gender on the velocity component of power production. This gender specific decline in optimal shortening velocity has also been observed elsewhere, although it has not been associated with functional outcomes (Valour et al., 2003). Despite not replicating the association with gender specific deterioration of velocity, the conclusions of these earlier studies combined with our results suggest that the dynamic aspect of muscle performance becomes increasingly more important for preserving function with age.

Our results add to the evidence that evaluation of muscle performance in dynamic conditions may be more sensitive than slow or isometric torque measurements for detecting weakness (Clark and Fielding, 2011). It may be that isometric assessments are less sensitive because they allow sufficient time for motor units to be recruited, excitation–contraction coupling to occur, and for tendons to become fully taut for optimal force transmission. In contrast, these force producing mechanisms may not have time to become fully engaged during dynamic assessments in older adults, leading to a more dramatic reduction in performance. Indeed, aging has previously been shown to be accompanied by slowing of neuromuscular activation (Clark et al., 2010), declines in the integrity of the neuromuscular junction (Deschenes et al., 2010), excitation–contraction uncoupling (Boncompagni et al., 2006), altered muscle fiber

contractile properties (Ng and Kent-Braun, 1999; Roos et al., 1999), and altered architecture and compliance of muscle and tendon (Maganaris et al., 2004; Morse et al., 2005; Narici and Maganaris, 2007).

Lastly, as power has been noted to be a predictor of functional limitation with age, our results support the growing body of evidence that power, with specific attention to the contribution of velocity, is a critical component in the design of intervention strategies for aging individuals (Henwood and Taaffe, 2005; Sayers and Gibson, 2010). However, only with in depth knowledge of the individual contributions of both force and velocity can interventions be tailored to optimize the most influential component. Our findings have important implications for those researchers and clinicians looking to most positively affect functional outcomes in older adults. Based upon our results, strategies should be employed to maximize velocity in physical activity interventions in older adults. Indeed, it has been demonstrated that high-velocity training can increase peak power (Fielding et al., 2002) and facilitate significant improvements in functional outcomes (Henwood and Taaffe, 2005). Moreover, specific improvements in the velocity component of power production have been demonstrated with short term training protocols in older, but not young, subjects (Petrella et al., 2007). Further research must be conducted to determine the optimal parameters for an intervention that targets age-related changes in dynamic muscle performance.

One limitation of this study is that TORs and VEL only accounted for about half of the variability in PWRs for the MH and OML groups. One likely explanation for this is differences in the neuromechanics of each of the three tasks that we assessed. That is, TORs was assessed with isometric contractions, VEL with isotonic contraction and PWRs with isokinetic contractions. This factor, plus the normal variability of maximal voluntary motor performance in humans, likely account for the majority of the unexplained variability.

5. Conclusion

These findings from three distinct groups of adults – middle aged healthy, older healthy, and older mobility limited – demonstrate differential contributions of force and velocity to the measurement of power and functional outcomes in an aging population. After accounting for muscle size, our findings identify velocity as the more significant determinant of power production and functional ability in older adults, especially in older adults with mobility limitations. These findings indicate the need for additional research to identify the specific neural and muscular mechanisms related to impaired power and functional task performance as well as to identify the optimal parameters of training interventions to prevent, or restore, loss of dynamic muscle performance.

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Abbreviations

MH	middle aged healthy
OH	older healthy
OML	older mobility limited

TORa	absolute torque
TORs	specific isometric torque
PWRa	absolute power
PWRs	specific power
VEL	velocity at 40% 1RM

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Fig. 1.

Regression analysis of specific power @180°/s. (A) Specific power @180°/s plotted against Keiser velocity @40% 1RM and isometric specific torque for MH; (B) specific power @180°/s plotted against Keiser velocity @40% 1RM and isometric specific torque for OH and (C) specific power @180°/s plotted against Keiser velocity @40% 1RM and isometric specific torque for OML.

Table 1

Means and standard deviations for torque, velocity and power.

Variable	MH mean (SD)	OH mean (SD)	OML mean (SD)
Torque (Nm)	154.59 (36.35)	137.53 (54.73)	114.76 (40.60)
Specific torque (Nm/cm ²)	2.46 (0.63)	2.55 (0.55)	2.50 (0.605)
Velocity @40% RM (radians/s)	5.64 (1.27)	4.83 (1.22)	3.88 (1.19)
Power @180°/s (watts)	215.04 (85.64)	173.28 (86.64)	119.39 (50.16)
Specific power (watts/cm ²)	3.35 (1.10)	3.15 (1.06)	2.60 (0.82)

Table 2

Regression analysis for specific power (PWRs) at 180°/s.

	Parameter estimate (SE)	R ²	Partial R ²
MH		0.55	
Constant	−0.207 (1.05)		–
Torque	0.914 (.287) ^a		0.30
Velocity	0.230 (0.14)		0.13
Gender (F)	−0.124 (0.187)		–
OH		0.89	
Constant	−1.97 (0.83)		–
Torque	0.967 (.257) ^a		0.36
Velocity	0.559 (0.143) ^a		0.40
Gender	0.258 (0.175)		–
OML		0.54	
Constant	0.535 (0.645)		–
Torque	0.190 (0.257)		0.01
Velocity	0.407 (0.127) ^a		0.13
Gender	0.123 (0.143)		–

^aIndicates p<0.05.

Table 3

Regression analysis: results for functional outcomes.

	Multiple chair rise parameter estimate (SE)	Stair climb parameter estimate (SE)
MH		
Constant	18.62 (9.24)	4.92 (1.86)
Torque	-0.11 (1.55)	0.26 (0.31)
Velocity	-0.25 (0.75)	-0.051 (0.15)
Body weight (kg)	0.044 (0.079)	-0.0044 (0.016)
Gender (F)	0.29 (1.20)	0.27 (0.24)
R ²	0.027	0.15
OH		
Constant	29.93 (5.89)	4.89 (1.09)
Torque	0.15 (1.92)	-0.13 (0.35)
Velocity	-0.89 (1.02)	-0.12 (0.19)
Body weight (kg)	-0.029 (0.062)	0.022 (0.011)
Gender	1.38 (1.26)	0.43 (0.23)
R ²	0.32	0.25
OML		
Constant	33.22 (13.11)	8.64 (4.29)
Torque	0.15 (2.48)	1.025 (0.8009)
Velocity	-5.12 (1.19) **	-0.904 (0.39) **
Body weight (kg)	0.25 (0.17)	-0.0031 (0.056)
Gender	1.21 (1.49)	-0.18 (0.48)
R ²	0.59	0.29

** Indicates p<0.05.