

Lower extremity muscle quality and gait variability in older adults

SUNGHOON SHIN¹, RUDY J. VALENTINE², ELLEN M. EVANS³, JACOB J. SOSNOFF

¹Kinesiology and Community Health, University of Illinois at Urbana-Champaign, 906 S. Goodwin Ave, Urbana, IL 61801, USA

²Diabetes and Metabolism Research Unit, Boston University School of Medicine, Boston, MA, USA

³Kinesiology, University of Georgia, Athens, GA, USA

Address correspondence to: J. J. Sosnoff. Tel: (+1) 217 714 6237; Fax: (+1) 217 244 7322. Email: jsosnoff@illinois.edu

Abstract

Background: it is not clear if gait variability is linked to muscle strength or muscle quality (MQ). This study examined the relation between leg strength and lower extremity MQ and gait variability in healthy ambulatory older adults.

Methods: seventy-two older adults (43 females and 29 males; age: 69.5 ± 6.1 years) underwent assessments of gait, leg strength and body composition. Leg strength was assessed with an isokinetic dynamometer and body composition by dual-energy X-ray absorptiometry (DXA). MQ was calculated from the information muscle strength and body composition. Gait was assessed by having the subjects walk down a pressure sensitive walkway at self-selected normal speed. Variability of spatial and temporal parameters of gait was calculated.

Results: there were minimal correlations between muscle strength and spatial parameters. However, both lower leg and upper leg MQ were negatively associated with spatial ($r^2 = -0.24$ to -0.49 , $P < 0.05$) and temporal gait variability ($r^2 = -0.27$ to -0.35 , $P < 0.05$). Also, lower leg MQ was found to be a better predictor of gait variability than upper leg MQ.

Conclusions: the results highlight that MQ may be an important determinant of gait function, even in healthy older adults.

Keywords: ageing, locomotion, muscle strength, consistency

It is well established that with advanced age there are increases in motor variability [1]. Increases in motor variability, particularly in gait, are associated with the adverse events of advanced age [2], including increased risk of falls [3, 4] and future mobility disability [3, 5]. Variability in step width [6], step length [7] and double support time (DST) [7] are all important predictors of locomotion in older adults. Despite the wealth of information concerning motor variability and ageing, reports specific to the mechanisms contributing to ageing and gait variability have been inconsistent [4, 5, 8–10].

Sosnoff and Newell [11] have theorised that age-related increases in motor variability result from declines in muscular strength, as evidenced by laboratory-based manual motor tasks. Congruent with this proposition is the association between lower-body strength and performance-based gait tasks [12, 13]. Additionally, lower leg muscle power has been found to be related to performance-based gait tasks in older adults [14]. However, these investigations relied solely on time to completion and do not quantify spatio-temporal markers of gait nor gait variability. Also, previous

studies have been limited to hand-grip or knee-extensor (quadriceps) strength [15, 16].

Under walking conditions, body mass, or the load carried during ambulation, has a negative impact on gait [17], whereas mineral-free lean mass (MFLM) in the legs appears to be a determinant of physical function in the elderly [18]. Furthermore, leg muscle quality (MQ), defined as muscle strength expressed relative to lean mass [19], has been shown to be an important predictor of mobility in older adults [19, 20]. Loss of MQ with age represents an inappropriate change in strength not accounted for by loss of muscle mass, likely caused by neuromuscular alterations, which may be relevant to changes in gait function as well (Supplementary data are available in *Age and Ageing* online).

Although age-related increases in gait variability and declines in lower limb muscle strength affect mobility, there is limited information concerning MQ in this context. Consequently, the aims of this study were to (i) examine the relation between (a) leg strength and (b) lower extremity MQ and gait variability in healthy ambulatory older adults self-selected normal speed and (ii) subsequently explore if upper

(thigh) and/or lower (shank) leg MQ is a stronger predictor of gait variability. We hypothesised that MQ (versus muscle strength) would have a stronger association with gait variability.

Methodology

Participants

Seventy-two community-dwelling older adults (43 females and 29 males) participated in the present study. Participants were recruited through local advertisements and word of mouth. Individuals reporting neuromuscular diseases, including multiple sclerosis or Parkinson's disease, as well as anyone with joint replacements, were excluded from participation in the present study. During testing participants wore comfortable clothing and shoes appropriate for walking. All procedures of the study were approved by the University of Illinois at Urbana-Champaign Institutional Review Board (IRB #10400) and subjects provided written informed consent.

Body composition

Body composition was measured using dual-energy X-ray absorptiometry (DXA; Hologic Discovery, software version 12.7.3, Waltham, MA, USA). A multi-scan approach was used to quantify MFLM of the upper and lower legs. Two whole body scans were performed. The first was performed per manufacturer guidelines and involved bisecting the femoral neck to determine MFLM of the entire leg. The second involved determining a region of interest surrounding only the lower leg (upper border bisecting the knee joint). Mineral-free lean mass of the upper leg was calculated as the difference between the entire leg and lower leg regions.

Muscle strength

Muscular strength was assessed using an isokinetic dynamometer (Humac Norm, Computer Sports Medicine, Inc., Stoughton, MA, USA). Unilateral maximal isometric voluntary contractions at the knee (extension and flexion) and ankle (plantar-flexion and dorsi-flexion) were assessed on both legs. Positioning for the knee was set at a hip flexion angle of 85° and knee flexion of 45°, with the ankle joint positioned at a plantar-flexion angle of 20°. A familiarisation trial was performed for each joint action and, following a rest interval, three trials were performed, with the highest peak torque achieved recorded as the maximal voluntary contraction (MVC). Because MVCs by nature have a motivational influence, verbal encouragement was provided throughout each trial to maximise effort.

Muscle quality

MQ was defined as strength per MFLM of the corresponding muscle group(s). Specifically, MQ of the upper leg was

quantified as knee extension MVC + knee flexion MVC/MFLM of the upper legs (as derived from DXA), whereas MQ of the ankle was defined similarly using MVC of ankle dorsiflexion and plantarflexion per MFLM of the lower leg. Strength of both legs was summed and normalised to the combined MFLM (right-leg + left-leg) to calculate MQ [18].

Gait

Subjects walked along an 8.3 × 0.89-m sized gait mat, GAITRite electronic walkway (CIR systems, Inc.), in a self-selected normal-paced walk. The condition was completed twice. Participants began and finished walking 2 m from the mat to minimise acceleration and deceleration, respectively. Additionally, the initial and final steps of each trial were excluded from data analyses based on manufacturer suggestions. On average, 21 steps were analysed for each trial.

The spatial gait parameters, step and stride length and width were determined per manufacturer guidelines. The stride length was defined as the distance between two consecutive heel points and step length as the distance from heel centre of the current footprint to the heel centre of the opposite footprint. The stride width is the vertical distance from midline midpoint of one footprint to the line formed by midline midpoints of two footprints of the opposite foot, and the step width is the length from the midline midpoint of the current footprint to the midline midpoint of the previous footprint on the opposite foot.

Temporal gait parameters calculated were step, stride, swing, stance and DST. Step time is the time elapsed from first contact of one foot to first contact of the opposite foot and stride time is the time elapsed between the first contacts of two consecutive footfalls of the same foot. Swing time is the time elapsed between the last contact of the current footfall and the first contact of the next footfall of the same foot. Stance time is the time elapsed between the first and last contact of two consecutive footfalls on the same foot.

The period when both feet contact the floor, is DST. Each step from both legs was accumulated to calculate each parameter, rather than for the left and right legs separately. Gait variability was determined by calculating intra-individual SD of each temporal and spatial gait parameters.

Statistical analyses

Means, standard deviation and distribution statistics were calculated, and normality was tested by the Shapiro–Wilk test ($P > 0.05$). Partial correlations and step-wise linear regression controlling for sex, age and normalised gait speed were conducted to assess the associations between (i) muscle strength and (ii) MQ with gait characteristics, and the relative contribution of upper and lower leg MQ to gait variability. All data were analysed using SPSS version 17.0

(SPSS Inc., Chicago, IL, USA). Significance was set at $P \leq 0.05$.

Results

Spatial and temporal markers of gait

Subject demographics, leg strength and MQ are summarised in Table 1. The average and intra-individual variability (SD) of the gait parameters are presented in Table 2.

Muscle strength, MQ and intra-individual gait variability

A positive significant correlation was found between muscular strength and gait variability; knee extension MVC with step width during normal-paced walking ($r = 0.29$, Table 3). MQ was negatively associated with a total of 10 measures of spatial and temporal gait variability, which was consistent across specific parameters of gait variability. Both lower and upper leg MQ were negatively correlated with the step length, the stride length and the step width in the spatial variability, with lower leg MQ having slightly stronger correlations than upper leg MQ (r range: -0.38 to -0.49 vs. -0.24 to -0.30). Similarly, both upper and lower leg MQ was inversely associated with temporal gait variability (step and stance time; r range = -0.27 to -0.33).

Stepwise linear regression analyses revealed that during normal-paced walking both lower and upper leg MQ were significant predictors of several, but different, parameters of gait variability. In the regression analysis, lower leg MQ

Table 2. Gait average and intra-individual spatial and temporal gait variability

		Gait average (mean)	Gait variability (SD)
Spatial parameters (cm)	Step length	71.5 \pm 7.8	2.3 \pm 0.7
	Support base	8.8 \pm 2.5	2.1 \pm 0.6
	Stride length	143.4 \pm 15.8	3.1 \pm 1.2
	Step width	72.5 \pm 7.8	2.3 \pm 0.7
	Stride width	10.7 \pm 2.8	1.9 \pm 0.5
Temporal parameters (ms)	Step time	524.0 \pm 690.0	14.0 \pm 4.0
	Stride time	1042.0 \pm 105.0	20.0 \pm 9.0
	Swing time	401.0 \pm 33.0	13.0 \pm 4.0
	Stance time	641.0 \pm 85.0	16.0 \pm 7.0
	Double support	234.0 \pm 45.0	14.0 \pm 3.0

Data presented in mean \pm SE.

was a predictor of both spatial and temporal gait variability. However, upper leg MQ was only a predictor of temporal variability. Neither upper nor lower leg MQ predicted variability in support base, stride width or DST.

Discussion

The novel aspect of this study was to assess the relationship between lower extremity MQ and gait variability in older adults. Although muscular strength has been associated with better performance on functional tasks [12, 13] as well as less variability in force output on laboratory-based manual motor tasks in older adults [11], examination of MQ, rather than simply muscle strength may be more appropriate. In fact, previous reports have cited MQ as the most important factor for physical function in obese frail older individuals [20, 21]. Furthermore, MQ better represents a disproportionate loss in strength not accounted for by reductions in muscle mass. Detriments in MQ are likely caused, at least in part, by neuromuscular changes, which may be relevant to ambulation and gait patterns.

In this study, it was observed that during normal walking, MQ was negatively associated with intra-individual gait variability, whereas absolute muscle strength was not. These findings align with but also extend the age-variability theory that asserts that the age-related increases in motor variability are due in part to specific muscular strength deficits [11]. In contrast to previous reports of an inverse relationship between knee-extensor (quadriceps) strength and temporal gait variability [14, 15], no such relationship existed in the current investigation. This may result from distinct methodology across investigations including different strength measures (spring gauge [22] and hand-held dynamometer [15]) were used and normalisation techniques [16, 22].

Gait as a dynamic spatiotemporal process has been quantified with various parameters. These parameters are broadly broken down into either temporal or spatial

Table 1. Subject characteristics (means \pm SD)

Characteristics	Total ($n = 72$)
Gender (females/males)	43/29
Age (years)	69.56 \pm 6.19
Weight (kg)	71.82 \pm 13.28
Height (cm)	167.50 \pm 10.08
MFLM _{leg}	16.41 \pm 4.12
Knee Ext MVC (N \cdot m)	251.4 \pm 80.6
Knee Ext MVC _{Height Normalised}	1.48 \pm 0.49
Knee Flex MVC (N \cdot m)	129.9 \pm 49.0
Knee Flex MVC _{Height Normalised}	0.77 \pm 0.30
Plantar MVC (N \cdot m)	83.1 \pm 28.5
Plantar MVC (N \cdot m) _{Height Normalised}	0.48 \pm 0.19
Dorsi MVC (N \cdot m)	57.1 \pm 16.1
Dorsi MVC (N \cdot m) _{Height Normalised}	0.33 \pm 0.11
MQ _{lower leg} (N \cdot m/kg)	25.8 \pm 5.7
MQ _{lower leg} (N \cdot m/kg) _{Height Normalised}	0.21 \pm 0.04
MQ _{upper leg} (N \cdot m/kg)	35.7 \pm 6.1
MQ _{upper leg} (N \cdot m/kg) _{Height Normalised}	0.15 \pm 0.04
Normalised gait speed(m/s)	1.51 \pm 0.32

MQ, isometric muscle quality; MFLM_{leg}, leg mineral free lean mass; Normalised gait speed, gait speed/leg length; KneeExtMVC, peak knee extension torque; KneeFlexMVC, peak knee flexion torque; PlantarMVC, peak plantarflexion torque; DorsiMVC, peak dorsiflexion torque.

Table 3. Correlation coefficients (*r*) between muscle quality and intra-individual spatial and temporal gait variability (SD) in each condition

Parameters	Intra-individual spatial gait variability (SD)					Intra-individual temporal gait variability (SD)				
	Step length	Stride length	Support base	Step width	Stride width	Step time	Stride time	Swing time	Stance time	Double support time
MQ _{lower leg}	−0.38**	−0.49**	0.02	−0.47**	−0.06	−0.29*	−0.20	−0.15	−0.29*	−0.17
MQ _{upper leg}	−0.24*	−0.30*	0.01	−0.26*	0.01	−0.27*	−0.20	−0.05	−0.33*	−0.07
KneeExtMVC	0.25	0.22	0.17	0.29*	0.16	0.09	−0.01	0.08	0.15	0.09
KneeFlexMVC	0.08	0.04	0.12	0.18	0.11	0.06	0.02	0.08	0.05	−0.12
PlantarMVC	0.01	−0.12	0.19	0.15	0.16	0.15	0.07	0.02	0.08	−0.22
DorsiMVC	−0.06	0.01	0.15	0.12	0.10	0.00	−0.09	0.07	−0.02	−0.09

All analyses were controlled for sex, age and normalised gait speed.

*A significant correlation ($P < 0.05$).

**A significant correlation ($P < 0.01$).

measures of gait, and have been used to clarify factors affecting gait. Variability of various parameters may imply different underlying mechanisms [3, 6]. In the present study, MQ was inversely associated with intra-individual variability in the stride length and stance time. This is an intriguing observation because stance time and stride length variability have been found to be associated with mobility disability and falls in older adults [3, 16, 23]. Our results highlight the importance of MQ for having the potential to favourably impact stance time and step width variability, which ultimately may enhance maintenance of physical function.

The current results demonstrate that MQ is a meaningful factor in determining the variability of gait in older adults. The present data are novel and extend previous work regarding physical function [19], suggesting that MQ, rather than absolute strength, may be more influential in minimising gait variability. It has been noted that decrements in lower limb strength result in increases in risk for falling [24], and that strength may be a mediating factor of the association between gait variability and fall risk [16, 25]. It remains to be investigated if MQ is a mediating factor of the association between gait variability and fall risk.

The present study is not without limitations. First, the gait outcomes from the GAITrite system are based on a limited number of steps (21) in a repeated fashion, and do not consider other important variables such as joint angle [22]. Although repeated walks may result in increased gait variability as compared to continuous [26], this type of protocol used here may better emulate typical walking patterns of older adults [27]. Second, the gait variability from spatial and temporal parameters was derived by combination of left and right steps. Finally, the strength measures included in the current study were limited to isometric MVCs of the ankle and knee. An assessment of muscle power could have strengthened the current study, as leg power has been reported to influence mobility [28]. Furthermore, several other muscle groups are actively involved in ambulation, most notably the core muscles and hip flexors, which were not

assessed here. Additionally, the appropriate definition of MQ is a topic of ongoing debate [18]. Within the current investigation MQ was defined as muscle strength expressed relative to lean mass. This definition does not take into account the amount of neural activation. Finally, this study was limited to normal-paced walking. Added challenges, such as navigating obstacles and changes in grade or walking surface, may more closely emulate tasks encountered in daily life and provide additional insight into strategies for fall prevention.

In conclusion our novel data suggest that: lower extremity MQ, but not muscle strength, of older adults is inversely associated with intra-individual spatial and temporal gait variability; and both upper and lower leg MQ are independently associated with intra-individual gait variability. Further work is needed to evaluate whether increasing lower extremity MQ will reduce gait variability towards the end of reducing physical disability and fall risk in older adults.

Key points

- Lower extremity MQ, but not muscle strength, of older adults is inversely associated with intra-individual spatial and temporal gait variability.
- Both upper and lower leg MQ are independently associated with intra-individual gait variability.

Conflicts of interest

None declared.

Supplementary data

Supplementary data mentioned in the text is available to subscribers in *Age and Ageing* online.

References

- Newell KM, Vaillancourt DE, Sosnoff JJ. Aging, complexity and motor performance. In: Birren JE, Schaie KW eds. *Handbook of the Psychology of Aging*. London: Academic Press, 2006; 163–82.
- Lipsitz LA. Dynamics of stability the physiologic basis of functional health and frailty. *J Gerontol A Biol Med Sci* 2002; 57: 115–25.
- Brach JS, Studenski SA, Perera S, VanSwearingen JM, Newman AB. Gait variability and the risk of incident mobility disability in community-dwelling older adults. *J Gerontol A Biol Med Sci* 2007; 62: 983.
- Hausdorff JM, Edelberg HK, Mitchell SL, Goldberg AL, Wei JY. Increased gait unsteadiness in community-dwelling elderly fallers. *Arch Phys Med Rehabil* 1997; 78: 278–83.
- Grabner PC, Biswas ST, Grabner MD. Age-related changes in spatial and temporal gait variables. *Arch Phys Med Rehabil* 2001; 82: 31–5.
- Brach JS, Studenski S, Perera S, VanSwearingen JM, Newman AB. Stance time and step width variability have unique contributing impairments in older persons. *Gait Posture* 2008; 27: 431–9.
- Mbourou GA, Lajoie Y, Teasdale N. Step length variability at gait initiation in elderly fallers and non-fallers, and young adults. *Gerontology* 2003; 49: 21–6.
- Callisaya ML, Blizzard L, McGinley JL, Schmidt MD, Srikanth VK. Sensorimotor Factors affecting gait variability in older people—population-based study. *J Gerontol A Biol Sci Med Sci* 2010; 65A: 386–92.
- Gabell A, Nayak USL. The effect of age on variability in gait. *J Gerontol* 1984; 39: 662–6.
- Owings TM, Grabner MD. Variability of step kinematics in young and older adults. *Gait Posture* 2004; 20: 26–9.
- Sosnoff JJ, Newell KM. Are age-related increases in force variability due to decrements in strength? *Exp Brain Res* 2006; 174: 86–94.
- Lamoureux EL, Sparrow WA, Murphy A, Newton RU. The relationship between lower body strength and obstructed gait in community-dwelling older adults. *J Am Geriatr Soc* 2002; 50: 468.
- Puthoff ML, Nielsen DH. Relationships among impairments in lower-extremity strength and power, functional limitations, and disability in older adults. *Phys Ther* 2007; 87: 1334.
- Bean JF, Kiely DK, LaRose S, Goldstein R, Frontera WR, Leveille SG. Are changes in leg power responsible for clinically meaningful improvements in mobility in older adults? *J Am Geriatr Soc* 2010; 58: 2363–8.
- Callisaya ML, Blizzard L, Schmidt MD, McGinley JL, Lord SRSrikanth VK. A population-based study of sensorimotor factors affecting gait in older people. *Age Ageing* 2009; 38: 290–5.
- Hausdorff JM, Rios DA, Edelberg HK. Gait variability and fall risk in community-living older adults: a 1-year prospective study. *Arch Phys Med Rehabil* 2001; 82: 1050–6.
- Morrison SC, Durward BR, Watt GF, Donaldson MDC. The influence of body mass on the temporal parameters of pre-pubescent gait. *Gait Posture* 2008; 27: 719–21.
- Visser M, Deeg DJH, Lips P, Harris TB, Bouter LM. Skeletal muscle mass and muscle strength in relation to lower-extremity performance in older men and women. *J Am Geriatr Soc* 2000; 48: 381.
- Misic MM, Rosengren KS, Woods JA, Evans EM. Muscle quality, aerobic fitness and fat mass predict lower-extremity physical function in community-dwelling older adults. *Gerontology* 2007; 53: 260–6.
- Villareal DT, Banks M, Siener C, Sinacore DR, Klein S. Physical frailty and body composition in obese elderly men and women. *Obesity Res* 2004; 12: 913–20.
- Maffiuletti N, Jubeau M, Munzinger U *et al.* Differences in quadriceps muscle strength and fatigue between lean and obese subjects. *Eur J Appl Physiol* 2007; 101: 51–9.
- Kang HG, Dingwell JB. Effects of walking speed, strength and range of motion on gait stability in healthy older adults. *J Biomech* 2008; 41: 2899–905.
- Nakamura T, Meguro K, Sasaki H. Relationship between falls and stride length variability in senile dementia of the Alzheimer type. *Gerontology* 1996; 42: 108–13.
- Hsiao-Wecksler ET. Biomechanical and age-related differences in balance recovery using the tether-release method. *J Electromyogr Kinesiol* 2008; 18: 179–87.
- Owings TM, Grabner MD. Step width variability, but not step length variability or step time variability, discriminates gait of healthy young and older adults during treadmill locomotion. *J Biomech* 2004; 37: 935–8.
- Paterson KL, Lythgo ND, Hill KD. Gait variability in younger and older adult women is altered by overground walking protocol. *Age Ageing* 2009; 38: 745–8.
- Orendurff MS, Schoen JA, Bernatz GC, Segal AD, Klute GK. How humans walk: Bout duration, steps per bout, and rest duration. *J Rehabil Res Dev VA Prosth Res Dev Center* 2008; 45: 1077–89.
- Bean JF, Leveille SG, Kiely DK, Bandinelli S, Guralnik JM, Ferrucci L. A comparison of leg power and leg strength within the InCHIANTI Study: which influences mobility more? *J Gerontol A Biol Sci Med Sci* 2003; 58: M728–33.

Received 26 July 2011; accepted in revised form 22 December 2011