Published in final edited form as:

Arch Gerontol Geriatr. 2012 September ; 55(2): 474–479. doi:10.1016/j.archger.2012.04.004.

Age-associated gait patterns and the role of lower extremity strength—results from the Baltimore Longitudinal Study of Aging

Seung-uk Ko¹, Sari Stenholm², E. Jeffrey Metter³, and Luigi Ferrucci³

¹Department of Mechanical Engineering, Chonnam National University, Yeosu, South Korea

²Department of Health, Functional Capacity and Welfare, National Institute for Health and Welfare, Turku, Finland ³Clinical Research Branch, NIA, Baltimore, MD, USA

Abstract

The aim of the present study was to examine differences in gait characteristics across the adult lifespan and to test the hypothesis that such differences are attributable at least in part to the decline in muscle strength. The data presented here are from 190 participants of the Baltimore Longitudinal Study of Aging (BLSA) aged from 32 to 93 years. Based on two age thresholds that best capture the effect of age on walking speed, participants were divided into three age groups: middle-age (32–57 years; N=27), old-age (58–78 years; N=125), and oldest-age (79–93 years; N=38). Participants were asked to walk at their preferred and maximum speeds while recorded with 3D gait analysis system. In addition, maximum isokinetic knee extensor strength was assessed. While walking at preferred speed, range of motion (ROM) and mechanical work expenditure (MWE) of the ankle were lower within middle-age ($p < 0.001$, $p = 0.047$, respectively), while hip ROM and MWE were lower ($p = 0.006$) and higher ($p < 0.001$), respectively within oldest-age with older age. Deterioration in ankle function during customary walking initiates already at middle-age. Differences in the maximum walking speed and ankle ROM between middle-age and old-age were explained by knee strength.

Keywords

Aging in gait; Adult lifespan; Knee strength; Ankle function; Stride width

Introduction

Customary walking is an essential activity for maintaining autonomous and independent living. Numerous studies have found that gait performance declines with aging (Callisaya et al., 2009; Kwon et al., 2001; McGibbon and Krebs, 2004) and the declines are strongly associated with development of mobility limitation and further disability (Guralnik et al.,

© 2012 Elsevier Ireland Ltd. All rights reserved.

Contact information for the corresponding author: Seung-uk Ko, Ph.D., Assistant professor, Department of Mechanical Engineering, Chonnam National University, 50 Daehak-ro, Yeosu, Jeonnam, 550-749, SOUTH KOREA, Mobile phone : 82-10-2991-8317, Fax: 82-61-659-3289, seunguk.ko@gmail.com.

Conflict of interest

All the authors declare that no financial or personal relationships were conducted with other people or organizations that could inappropriately influence or bias this work.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

2000; Simonsick et al., 2008). Prior studies revealed that older age is associated with slower gait speed, shorter stride length (Judge et al., 1996; Ko et al., 2010), wider stride width (Dean et al., 2007; Schrage et al., 2008), and lower mechanical joint power and work in the lower extremity (DeVita and Hortobagyi, 2000; Ko et al., 2009; McGibbon and Krebs, 2004). However, it is still not clear from prior studies whether changes in gait characteristics that become evident in older individuals can be already detected at relatively younger age. Understanding trajectory of change may provide clues on the mechanism responsible for those changes and suggest possible preventative strategies for early ages. For example, it is widely acknowledged that lower extremity muscle strength decreases with aging and muscle strength is related to walking speed, although the relationship is not linear (LaRoche et al., 2011). Thus, it is reasonable to hypothesize that a decrease of muscle strength is linked with changes in gait characteristics but evidence to support this hypothesis is scarce and limited to spatiotemporal parameters reporting slower gait speed associated with lower knee strength (Callisaya et al., 2009; Kwon et al., 2001).

The aim of the present study was to examine differences in gait characteristics across the adult lifespan and to test the hypothesis that such differences are attributable at least in part to the declines in muscle strength that occurs with aging. We analyzed walking tasks performed at the preferred and maximum speeds because previous literatures suggest that walking at maximum speed challenges functional reserve and therefore may reveal initial impairments that do not emerge when walking at usual pace (Judge et al., 1996; Kerrigan et al., 1998). With two cut points of ages, which most differentiate maximum gait speed (Muggeo, 2003), three age groups were obtained. The relationship of gait patterns and knee strength was examined within and between three age groups in order to understand the nature of the relationship in different periods of age.

Methods

Study population

The data were obtained from 190 adult participants of the Baltimore Longitudinal Study of Aging (BLSA; longitudinal cohort study conducted by NIH, NIA). Participants were between 32 to 93 years of age and were studied in the BLSA gait laboratory between January and December of 2008. Participants who did not have hip or knee joint prosthesis, osteoarthritis (OA), severe joint pain, or history of stroke or Parkinson's disease, who could follow instructions and safely complete a 10-meter walk unaided, and who completed a maximum isokinetic knee extensor strength test were included in this study. Three age groups based on two age thresholds (Muggeo, 2003), which most differentiate maximum gait speed, were obtained to identify subtle age effects on gait patterns in different age levels: middle-age (32–57 years; N=27), old-age (58–78 years; N=125), and oldest-age (79–93 years; N=38). The BLSA protocol was approved by the Medstar Research Institution Review Board. Participants were given a detailed description of the study and consented to participate.

Gait measurement

The protocol for gait analysis used in this study has been described elsewhere (Ko et al., 2011). Briefly, reflective markers are placed on participants at 20 anatomical landmarks: anterior and posterior superior iliac spines, medial and lateral knees, medial and lateral ankles, toe (second metatarsal head), heel, and lateral malleoli over the mid-femur and mid-tibia. A Vicon 3D motion capture system with 10 digital cameras (Vicon 612 system, Oxford Metrics Ltd., Oxford, U.K.) measured the 3D locations of all markers on the landmarks of lower extremity segments (60 Hz sampling frequency). During the gait test, ground reaction forces were measured with two staggered force platforms (Advanced

Mechanical Technologies, Inc., Watertown, MA, USA; 1080 Hz sampling frequency). After all markers were positioned on the skin and non-reflective tight-fitting spandex tights, participants were asked to walk across a 10-m long laboratory walkway at the preferred speed and at the fastest speed without running (maximum speed).

Knee strength

Maximum isokinetic knee extensor strength was measured using the Kinetic Communicator isokinetic dynamometer (Kin-Com model 125E, version 3.2, Chattanooga Group, Chattanooga, TN). Concentric knee extensor strength was measured at angular velocity of 3.14 rad/s (180°/s) for the dominant leg over 60° of movement. Also, Eccentric knee extensor strength was measured at angular velocity of 0.52 rad/s (30°/s) to assess the eccentric knee joint kinetic behavior during stance. Three maximal efforts were performed separated by 30-s rest intervals, and the highest value was used as the maximum isokinetic knee extensor strength (torque, N·m/kg, Table 1). Detailed procedures are described elsewhere (Duff-Raffaele et al., 1996; Lynch et al., 1999; Walsh et al., 2008).

Data process and statistical analysis

Gait parameters in kinematics and kinetics were measured and calculated as previously reported (Ko et al., 2009; Ko et al., 2007). Statistical analyses were performed with SAS 9.1 Statistical Package (SAS Institute, Inc., Cary, NC, USA). Spline regression models with split points at ages 57 and 78 were used to examine the effect of age on different gait patterns both overall and within each age group. This approach maximized the fit of the data with most distinguished gait speed between age-groups (Muggeo, 2003). Detailed model is depicted in Table 2. Generalized linear regression models (GLM) were used to compare mean values of gait parameters between age groups (Table 3) adjusted for gait speed, sex, weight, and height. Further, to examine the role of muscle strength on gait parameters within different age groups, knee strength was included in fully adjusted GLM as additional covariate. Statistical significance was defined as a *p*-value less than 0.05.

Results

Mean age for the study population was 68 years, ranging from 32 to 93 years. Other characteristics of participants in three age groups are summarized in Table 1. Maximum isokinetic knee concentric strength was significantly lower with older age ($p < 0.001$) with significant differences both between middle-age and old-age ($p < 0.001$) and old-age and oldest-age groups ($p = 0.012$). Age-associations for gait parameters in the preferred and maximum speed walking within three age groups were conducted with spline regression model adjusted with maximum isokinetic knee concentric strength, and summarized in Table 2. Older age was associated with slower gait speed within the old-age and oldest-age for preferred and maximum speed walking (for all $p < 0.001$). Stride width was lower within middle-age ($p = 0.010$), but higher within old-age ($p = 0.001$) with older age for a preferred speed walking. For preferred speed walking, sagittal plane ankle range of motions (ROM) was lower with older age within the middle-age and old-age groups ($p < 0.001$, $p = 0.017$, respectively), and sagittal plane hip ROM was lower with age within the old-age and oldest-age groups ($p = 0.005$, $p < 0.001$, respectively), and sagittal plane hip ROM was lower with age within oldest-age group ($p = 0.006$). Frontal plane ROM for the hip and ankle were lower only within oldest-age group for preferred speed walking ($p = 0.020$, $p < 0.001$, respectively). During preferred speed walking, sagittal plane MWE of hip within oldest-age group was higher ($p < 0.001$), while sagittal plane MWE of ankle within old-age group was lower ($p = 0.047$) with older age. Frontal plane hip MWE was significantly lower with older age within old-age group for both preferred and maximum speed walking ($p \leq 0.001$, for both).

In Table 3, the adjusted mean values of gait characteristics are compared between three age groups. Stride width for a maximum speed walking and ankle ROM in the sagittal plane for a preferred speed walking were significantly lower in old-age group compared to middle-age group ($p = 0.022, 0.012$, respectively). Noteworthy, many gait characteristics including spatiotemporal parameters, ROM for the hip, knee, and ankle and hip MWE in the frontal plane were significantly different between the old and oldest-age groups ($P < 0.05$ for all; Table 3), but not between the middle-age and old-age groups.

Finally, we examined whether gait pattern differences in different age levels could be explained by maximum knee strength in Table 3; p values with † and § mark indicate the differences between age groups can be explained by concentric and eccentric knee strength differences, respectively. This was done by introducing maximum knee strength as a potential mediator in the models testing the relationship between age and gait parameters. With additional adjustment of maximum concentric knee strength, significant difference for maximum gait speed between the middle-age and old-age groups ($P = 0.006$) disappeared ($P = 0.199$). Significant differences for ankle ROM in the sagittal plane for both comparisons of between the middle-age and old-age groups ($P = 0.012$) and between the old-age and oldest-age groups ($P = 0.019$) also disappeared after adjusting with maximum knee strength ($P = 0.123$, and 0.092 , respectively). Also, the difference of hip ROM in frontal plane between the old-age and oldest-age groups for both walking at preferred and maximum speeds ($P = 0.019$, and 0.039 , respectively) vanished after adjusting with maximum isokinetic knee extensor strength ($P = 0.100$, and 0.068 , respectively).

Discussion

Age-related changes in gait patterns were examined within and between three age groups including the middle-age (32–57 years), old-age (58–78 years) and oldest-age (79–93 years). Partially supporting our hypothesis, it was observed that gait performance decline is already evident at middle-age for ankle rotation and mechanical energy generated in the sagittal plane. In addition, we observed significant differences in the maximum walking speed and ankle ROM during walking at preferred speed walking between middle-age and old-age, which appear to be accounted for the reduced maximum concentric knee strength.

Although prior studies examined the age-associated patterns in gait characteristics, this is the first study to compare the gait characteristics and knee strength in a large population sample analyzed over a wide age range. Consistent with prior studies, we observed slower gait speed with older age for the walking at preferred and maximum speeds within the old-age and oldest-age groups (Judge et al., 1996; Ko et al., 2010; Olney et al., 1994). Interestingly, maximum walking speed was significantly different between the middle-age and old-age groups, while preferred walking speed was different only between the old-age and oldest-age groups. These findings from gait speed suggest that the deterioration of walking performance can be revealed at an early stage by challenging task such as walking at maximum speed.

Prior studies provided inconsistent results on age-associated patterns in stride width. Some studies reported wider stride width with older age (Beauchet et al., 2009; Dean et al., 2007; Schrager et al., 2008), but narrower stride width in older adults compared to younger adults have been reported as well (Blanke and Hageman, 1989). Similar to previous reports, our finding on stride width was inconsistent within different age groups. With older age, stride width in preferred speed walking was narrower within middle-age, while stride width within old-age was wider. We interpreted our finding as indicating that aging affects stride width differently at different ages, thus may explain the inconsistent results from previous reports.

However, the mechanistic nature of such different age effects remains puzzling and should be studied more in details in larger populations and possibly using longitudinal data.

We also showed that decline of ankle ROM in the sagittal plane was already evident in middle aged adults (Figure1-a) while knee joint and finally hip joint ROM reduction occurred progressively later for the old-age, and oldest-age groups. Significant declines of ROM in the frontal plane for the hip joint occurred in the oldest-age group (Figure1-b). These findings suggest that there is a progression in the effect of age on the kinematics of lower extremity in the sagittal and frontal plane. It is likely that these progressive changes have a compensatory nature but the mechanism underlying this compensation should be further examined.

Because MWE includes gait information of kinematics (angular velocity) and kinetics (joint moment) simultaneously, it is reasonable to consider MWE during stance as a proxy measure of gait-related mechanical energy consumption, which can characterize age-associated gait patterns within and between each age groups with functional meanings. Ankle MWE in the sagittal plane decreased significantly with age only in the middle age group and only in the preferred speed task. Given that ankle activity during customary walking is crucial for forward propulsion required for forward locomotion and transporting center of mass to the contralateral side, this finding of an early effect of age on ankle function (middle-age) is noticeable. Hip activity in the sagittal plane was higher in MWE while ROM was lower with older age within oldest-age group. The increment with age of hip mechanical energy in the oldest-age group is particularly interesting since many other gait parameters including gait speed, stride length, ROM of the hip and knee, and knee strength were significantly lower with older age in this late age period. Consistent with prior reports, this finding suggests that increased hip energy in late life has a compensatory value (Ko et al., 2009; Lewis and Ferris, 2008).

Finally, we found that by adjusting for maximum isokinetic knee extensor strength, the significant differences between age groups for the maximum gait speed, ankle ROM in the sagittal plane and hip ROM in the frontal plane were substantially reduced and were no longer statistically significant. These are consistent with studies showing that lower extremity muscle strength is strongly associated with gait speed (Kwon et al., 2001; Persch et al., 2009) and lower extremity functions (Misic et al., 2009) and also provide specific links between strength and lower extremity function. These results suggest that slower gait speed and lower ankle ROM in the sagittal plane for a preferred speed walking in older-age group compared to middle-age group can be due to limited knee strength. Also, lower knee strength can explain lower hip ROM in the frontal plane for oldest-age group compared to older-age group. Considering the significances of gait speed, ankle angular movement, and hip abduction and adduction in performance for customary walking, maximum knee strength can be an essential determinant factor for age-associated gait pattern modification throughout adult lifespan. However, adjustment for maximum knee extensor strength did not explain other gait parameter difference between age groups such as MWEs. Although it may be hypothesized that some changes in gait characteristics with age are unrelated to muscle function, other possibilities should also be considered. We only measured maximum isokinetic knee extensor strength, and thus unique measure may not be representative of other muscle groups, such as ankle plantar flexors and hip abductors, that are heavily involved in gait. In addition, other factors such as self-efficacy, confidence (McAuley et al., 2007), and reaction time (Rogers et al., 2003) may partly explain the age group differences in gait patterns. Further intervention studies are needed to examine whether strengthening knee extensors, hip abductors and ankle plantar flexors could improve gait performance in different age groups.

The current study has limitations. First, the numbers of people within the middle-age and oldest-age were smaller than the number of people within the old-age. Second, due to the nature of cross-sectional study, we were unable to identify causality of age-associated gait patterns. The BLSA is currently collecting follow-up data of gait measures which will allow us to perform longitudinal studies in the future with more samples in the middle-age and oldest-age groups.

In conclusion, the current study suggests that gait speed decreases with age as the group means decrease from old-age to oldest-age for preferred walking speed and across all groups for maximum walking speed. It appears that this might be due to a decrease in the hip, knee, and ankle ranges of motion with the effect starting first at the ankle and moving up the limb to the hip. Result also suggests that gait performance declines for the maximum walking speed and ankle range of motion are related with maximum isokinetic knee extensor strength. Due to the lack of difference in the MWE it is difficult to say why these changes occur.

Acknowledgments

This research was supported entirely by the Intramural Research Program of the NIH, National Institute on Aging. Data for these analyses were obtained from the Baltimore Longitudinal Study of Aging, a study performed by the National Institute on Aging.

References

- Beauchet O, Allali G, Annweiler C, Bridenbaugh S, Assal F, Kressig RW, Herrmann FR. Gait Variability among Healthy Adults: Low and High Stride-to-Stride Variability Are Both a Reflection of Gait Stability. *Gerontology*. 2009
- Blanke DJ, Hageman PA. Comparison of gait of young men and elderly men. *Physical therapy*. 1989; 69:144–148. [PubMed: 2913584]
- Callisaya ML, Blizzard L, Schmidt MD, McGinley JL, Lord SR, Srikanth VK. A population-based study of sensorimotor factors affecting gait in older people. *Age and Ageing*. 2009; 38:290–295. [PubMed: 19264860]
- Dean JC, Alexander NB, Kuo AD. The effect of lateral stabilization on walking in young and old adults. *IEEE Transactions on Biomedical Engineering*. 2007; 54:1919–1926. [PubMed: 18018687]
- DeVita P, Hortobagyi T. Age causes a redistribution of joint torques and powers during gait. *Journal of applied physiology*. 2000; 88:1804–1811. [PubMed: 10797145]
- Duff-Raffaele M, Kerrigan DC, Corcoran PJ, Saini M. The proportional work of lifting the center of mass during walking. *American Journal of Physical Medicine and Rehabilitation*. 1996; 75:375–379. [PubMed: 8873706]
- Guralnik JM, Ferrucci L, Pieper CF, Leveille SG, Markides KS, Ostir GV, Studenski S, Berkman LF, Wallace RB. Lower extremity function and subsequent disability: consistency across studies, predictive models, and value of gait speed alone compared with the short physical performance battery. *The journals of gerontology Series A, Biological sciences and medical sciences*. 2000; 55:M221–231.
- Judge JO, Davis RB 3rd, Ounpuu S. Step length reductions in advanced age: the role of ankle and hip kinetics. *The journals of gerontology Series A, Biological sciences and medical sciences*. 1996; 51:M303–312.
- Kerrigan DC, Todd MK, Della Croce U, Lipsitz LA, Collins JJ. Biomechanical gait alterations independent of speed in the healthy elderly: evidence for specific limiting impairments. *Archives of Physical Medicine and Rehabilitation*. 1998; 79:317–322. [PubMed: 9523785]
- Ko S, Hausdorff JM, Ferrucci L. Age-associated differences in the gait pattern changes of older adults during fast-speed and fatigue conditions: results from the Baltimore longitudinal study of ageing. *Age and Ageing*. 2010

- Ko S, Ling SM, Winters J, Ferrucci L. Age-related mechanical work expenditure during normal walking: the Baltimore Longitudinal Study of Aging. *Journal of Biomechanics*. 2009; 42:1834–1839. [PubMed: 19646705]
- Ko SU, Gunter KB, Costello M, Aum H, MacDonald S, White KN, Snow CM, Hayes WC. Stride width discriminates gait of side-fallers compared to other-directed fallers during overground walking. *Journal of aging and health*. 2007; 19:200–212. [PubMed: 17413131]
- Ko SU, Stenholm S, Chia CW, Simonsick EM, Ferrucci L. Gait pattern alterations in older adults associated with type 2 diabetes in the absence of peripheral neuropathy--results from the Baltimore Longitudinal Study of Aging. *Gait & posture*. 2011; 34:548–552. [PubMed: 21873064]
- Kwon IS, Oldaker S, Schrager M, Talbot LA, Fozard JL, Metter EJ. Relationship between muscle strength and the time taken to complete a standardized walk-turn-walk test. *The journals of gerontology Series A, Biological sciences and medical sciences*. 2001; 56:B398–404.
- LaRoche DP, Millett ED, Kralian RJ. Low strength is related to diminished ground reaction forces and walking performance in older women. *Gait and Posture*. 2011; 33:668–672. [PubMed: 21458271]
- Lewis CL, Ferris DP. Walking with increased ankle pushoff decreases hip muscle moments. *Journal of Biomechanics*. 2008; 41:2082–2089. [PubMed: 18606419]
- Lynch NA, Metter EJ, Lindle RS, Fozard JL, Tobin JD, Roy TA, Fleg JL, Hurley BF. Muscle quality. I. Age-associated differences between arm and leg muscle groups. *Journal of applied physiology*. 1999; 86:188–194. [PubMed: 9887130]
- McAuley E, Morris KS, Doerksen SE, Motl RW, Liang H, White SM, Wojcicki TR, Rosengren K. Effects of change in physical activity on physical function limitations in older women: mediating roles of physical function performance and self-efficacy. *Journal of the American Geriatrics Society*. 2007; 55:1967–1973. [PubMed: 18081672]
- McGibbon CA, Krebs DE. Discriminating age and disability effects in locomotion: neuromuscular adaptations in musculoskeletal pathology. *Journal of applied physiology*. 2004; 96:149–160. [PubMed: 12949019]
- Misic MM, Valentine RJ, Rosengren KS, Woods JA, Evans EM. Impact of training modality on strength and physical function in older adults. *Gerontology*. 2009; 55:411–416. [PubMed: 19590159]
- Muggeo VM. Estimating regression models with unknown break-points. *Stat Med*. 2003; 22:3055–3071. [PubMed: 12973787]
- Olney SJ, Griffin MP, McBride ID. Temporal, kinematic, and kinetic variables related to gait speed in subjects with hemiplegia: a regression approach. *Physical therapy*. 1994; 74:872–885. [PubMed: 8066114]
- Persch LN, Ugrinowitsch C, Pereira G, Rodacki AL. Strength training improves fall-related gait kinematics in the elderly: a randomized controlled trial. *Clinical biomechanics*. 2009; 24:819–825. [PubMed: 19716637]
- Rogers MW, Johnson ME, Martinez KM, Mille ML, Hedman LD. Step training improves the speed of voluntary step initiation in aging. *The journals of gerontology Series A, Biological sciences and medical sciences*. 2003; 58:46–51.
- Schrager MA, Kelly VE, Price R, Ferrucci L, Shumway-Cook A. The effects of age on medio-lateral stability during normal and narrow base walking. *Gait and Posture*. 2008; 28:466–471. [PubMed: 18400500]
- Simonsick EM, Newman AB, Visser M, Goodpaster B, Kritchevsky SB, Rubin S, Nevitt MC, Harris TB. Mobility limitation in self-described well-functioning older adults: importance of endurance walk testing. *The journals of gerontology Series A, Biological sciences and medical sciences*. 2008; 63:841–847.
- Walsh S, Liu D, Metter EJ, Ferrucci L, Roth SM. ACTN3 genotype is associated with muscle phenotypes in women across the adult age span. *Journal of applied physiology*. 2008; 105:1486–1491. [PubMed: 18756004]

(a) Ankle range of motion and mechanical work expenditure in the sagittal plane

(b) Hip range of motion and mechanical work expenditure in the frontal plane

Figure 1.

Age-associated declines in range of motion (ROM) and mechanical work expenditure (MWE) for ankle in the sagittal plane (a) and for hip in the frontal plane (b) for both walking task at preferred and maximum speed.*

* p values in figure are age-associated significances within age group from spline regression model with cut points in ages of 57 and 78. Only significant associations are shown.

Table 1

Characteristics of participants according to three age groups.

Characteristics of participants	Mean (SE) and proportion within age groups				P values in age group comparisons and trend		
	Middle-age 32 age 57 N = 27	old-age 58 age N = 125	78 age 93 N = 38	Oldest-age 79 age 93 N = 38	Middle-age vs. old-age	Old-age vs. Oldest-age	P for trend with age
Anthropometrical measurements							
Age, years	47.96 (1.05)	67.14 (0.49)		84.21 (0.88)	< 0.001	< 0.001	
Sex, women, %	50	51		42			
Height, meter	1.71 (0.02)	1.69 (0.01)		1.67 (0.01)	0.341	0.627	0.029
Weight, kg	79.69 (2.82)	77.65 (1.31)		72.04 (2.38)	0.791	0.100	0.021
Gait speed							
Preferred speed, m/s	1.21 (0.03)	1.17 (0.02)		0.96 (0.03)	0.455	< 0.001	< 0.001
Maximum speed, m/s	1.96 (0.06)	1.76 (0.03)		1.40 (0.05)	0.005	< 0.001	< 0.001
Maximum isokinetic knee extensor Strength							
Concentric strength, N·m / kg (in angular velocity at 180°/sec)	1.66 (0.07)	1.33 (0.03)		1.13 (0.06)	< 0.001	0.012	< 0.001
Eccentric strength, N·m / kg (in angular velocity at 30°/sec)	3.05 (0.14)	2.56 (0.07)		2.33 (0.13)	0.007	0.269	< 0.001

BMI = body mass index

SE = standard error

Table 2

Effect of age on gait parameters within age groups. (The last column shows the relationship between muscle strength and the same gait parameters)

Gait parameters	Association with age within age groups*										Association with maximum knee extensor strength
	Middle-age 32					Oldest-age 58					
	age	57	Old-age	58	age	78	Oldest-age	79	age	93	
	β_u	<i>p</i> value	β_h	<i>p</i> value	β_c	<i>p</i> value	β_d	<i>p</i> value	β_d	<i>p</i> value	
Spatiotemporal											
Gait speed, m/s	preferred	0.004	0.236	-0.008	<0.001	-0.022	<0.001	<0.001	0.103	<0.001	
	maximum	0.000	0.987	-0.017	<0.001	-0.034	<0.001	<0.001			
Stride Length, m	preferred	0.000	0.928	-0.003	<0.001	-0.010	<0.001	<0.001	0.046	0.003	
	maximum	-0.002	0.453	-0.002	0.149	-0.009	0.016	0.016			
Stride Width, cm	preferred	-0.087	0.010	0.073	0.001	0.003	0.956	0.956	0.248	0.466	
	maximum	-0.103	0.030	0.016	0.619	-0.042	0.631	0.631			
Range of motion (ROM) in the sagittal plane, deg.											
Hip	preferred	0.041	0.509	-0.057	0.167	-0.307	0.006	0.006	1.207	0.053	
	maximum	-0.017	0.844	0.001	0.989	-0.331	0.040	0.040			
Knee	preferred	-0.059	0.376	-0.124	0.005	-0.521	<0.001	<0.001	2.688	<0.001	
	maximum	0.044	0.631	-0.067	0.281	-0.580	<0.001	<0.001			
Ankle	preferred	-0.252	<0.001	-0.093	0.017	-0.106	0.309	0.309	1.137	0.053	
	maximum	-0.134	0.099	-0.110	0.044	-0.030	0.844	0.844			
Range of motion (ROM) in the frontal plane, deg.											
Hip	preferred	-0.058	0.096	-0.029	0.215	-0.144	0.020	0.020	1.202	<0.001	
	maximum	-0.045	0.357	-0.024	0.470	-0.173	0.055	0.055			
Knee	preferred	0.040	0.459	-0.061	0.089	-0.077	0.421	0.421	1.025	0.056	
	maximum	0.073	0.326	-0.065	0.192	0.106	0.442	0.442			
Ankle	preferred	0.083	0.116	-0.051	0.146	-0.321	<0.001	<0.001	0.196	0.712	
	maximum	0.094	0.198	-0.060	0.226	-0.267	0.052	0.052			
Total concentric MWE in the sagittal plane, 1000 × J/kg											
Hip	preferred	0.291	0.804	0.742	0.334	7.391	<0.001	<0.001	21.23	0.056	

Gait parameters	Association with age within age groups*							Association with maximum knee extensor strength	
	Middle-age 32			Old-age 58			Oldest-age 79		93
	β_a	p value	β_b	p value	β_c	p value	β_d	p value	
Knee	gait speed								
	maximum	0.586	0.718	0.646	1.749	0.560			
	preferred	0.689	0.388	0.348	-0.029	0.984	11.707		0.122
Ankle	maximum	1.050	0.342	-1.112	1.279	0.532			
	preferred	-1.810	0.047	-0.357	0.550	0.542	22.911		0.008
	maximum	-2.477	0.050	-0.359	-1.620	0.488			
Total concentric MWE in the frontal plane, $1000 \times \text{J/kg}$									
Hip	preferred	-0.154	0.737	-1.321	< 0.001	0.080	9.220		0.035
	maximum	0.425	0.050	-1.452	< 0.001	0.335			
Knee	preferred	-0.003	0.983	-0.035	0.694	0.516	0.978		0.441
	maximum	-0.133	0.472	0.094	0.447	0.092			
Ankle	preferred	0.220	0.159	0.002	0.983	0.606	1.298		0.380
	maximum	0.233	0.281	0.019	0.895	0.952			

* From a spline regression model as follows
 $E(x) = \beta_0 + \beta_1 \text{ age} + \beta_2 \text{ MaxSpeedWalk} \times \text{age} + \beta_3 \text{ MaxSpeedWalk} \times \text{spline01} \times \text{MaxSpeedWalk} + \beta_6 \text{ spline02} + \beta_7 \text{ spline02} \times \text{MaxSpeedWalk} + \beta_8 \text{ weight} + \beta_9 \text{ sex} + \beta_{10} \text{ height} + \beta_{11} \text{ MaxKneeStrength} + \beta_{12} \text{ speed}$ (except, speed itself) (where, MaxSpeedWalk: maximum speed walking; age : age before age < 58; spline01: age increment after age 58; spline02: age increment after age 79; MaxKneeStrength : Maximum isokinetic knee extensor strength)

	for preferred speed walking	for maximum speed walking
$\beta_a =$	β_1	$\beta_1 + \beta_3$
$\beta_b =$	$\beta_1 + \beta_4$	$\beta_1 + \beta_3 + \beta_4 + \beta_5$
$\beta_c =$	$\beta_1 + \beta_4 + \beta_6$	$\beta_1 + \beta_3 + \beta_4 + \beta_5 + \beta_6 + \beta_7$
$\beta_d =$	β_{11}	β_{11}

Table 3
Mean values of gait characteristics at preferred and maximum speed walking within three age groups.

Gait parameters for the walking at preferred and maximum speeds		Adjusted mean and SE within age groups						Comparisons between age groups	
		Middle-age 32 age = 27		Old-age 58 age = 125		Oldest-age 79 age = 38		Middle-age vs. Old-age	Old-age vs. Oldest-age
		Adjusted* mean	(SE)	Adjusted* mean	(SE)	Adjusted* mean	(SE)		
Spatiotemporal	gait speed								
	preferred	1.21	(0.03)	1.17	(0.02)	0.95	(0.03)	0.553	< 0.001
	maximum	1.95	(0.06)	1.76	(0.03)	1.40	(0.05)	0.009[†]	< 0.001
	preferred	1.25	(0.02)	1.23	(0.01)	1.15	(0.02)	0.651	< 0.001
Stride Length, m	maximum	1.52	(0.03)	1.48	(0.01)	1.33	(0.03)	0.321	< 0.001
	preferred	11.64	(0.45)	10.60	(0.21)	11.70	(0.42)	0.084	0.058
	maximum	11.84	(0.54)	10.27	(0.24)	10.47	(0.53)	0.022	0.940
Range of motion (ROM) in the sagittal plane, deg.	Hip	39.37	(0.76)	40.33	(0.35)	38.74	(0.70)	0.471	0.125
	maximum	47.10	(1.08)	46.70	(0.48)	43.28	(1.06)	0.937	0.012
	Knee	57.22	(0.94)	55.48	(0.43)	51.95	(0.87)	0.203	0.002
	maximum	59.60	(1.06)	58.83	(0.47)	54.95	(1.04)	0.773	0.003
	preferred	27.05	(0.82)	24.47	(0.38)	22.06	(0.76)	0.012[†]	0.019[†]
	maximum	26.38	(0.87)	25.30	(0.39)	21.73	(0.86)	0.482	< 0.001
Range of motion (ROM) in the frontal plane, deg.	Hip	11.16	(0.43)	10.41	(0.20)	9.15	(0.40)	0.250	0.019[†]
	maximum	13.41	(0.57)	12.84	(0.25)	11.29	(0.56)	0.629	0.039[†]
	Knee	10.77	(0.73)	10.88	(0.33)	9.58	(0.68)	0.989	0.220
	maximum	10.11	(0.77)	10.54	(0.34)	10.21	(0.75)	0.866	0.920
	preferred	9.32	(0.59)	9.45	(0.27)	7.17	(0.55)	0.975	0.001
	maximum	8.94	(0.67)	9.63	(0.30)	8.09	(0.65)	0.604	0.094

Gait parameters for the walking at preferred and maximum speeds		Adjusted mean and SE within age groups							Comparisons between age groups			
		Middle-age 32 age = 27		57 N	Old-age 58 age = 125		78 N =	Oldest-age 79 age = 38		93 N	Middle-age vs. Old-age	Old-age vs. Oldest-age
		Adjusted*		Adjusted*		Adjusted*		Adjusted*		P value		P value
gait speed		mean	(SE)	mean	(SE)	mean	(SE)	mean	(SE)	P value		
Total concentric MWE in the sagittal plane, $1000 \times \text{J/kg}$	Hip	preferred	179.99	(12.09)	175.49	(5.55)	193.52	(10.99)	0.938	0.330		
		maximum	313.29	(21.09)	332.38	(9.37)	355.05	(20.33)	0.681			
	Knee	preferred	99.55	(9.61)	105.85	(4.41)	116.68	(8.73)	0.819		0.528	
		maximum	169.33	(14.24)	161.55	(6.33)	142.88	(13.73)	0.869		0.445	
	Ankle	preferred	202.83	(11.02)	176.13	(5.05)	193.32	(10.01)	0.069		0.297	
		maximum	277.54	(15.87)	262.58	(7.05)	232.36	(15.30)	0.660		0.184	
Total concentric MWE in the frontal plane, $1000 \times \text{J/kg}$	Hip	preferred	93.04	(5.93)	83.96	(2.72)	64.74	(5.39)	0.339	0.006		
		maximum	92.28	(6.48)	88.61	(2.88)	57.80	(6.25)	0.860		< 0.001	
	Knee	preferred	10.87	(1.39)	11.01	(0.64)	10.70	(1.26)	0.995		0.976	
		maximum	16.56	(2.50)	16.55	(1.11)	16.24	(2.41)	0.999		0.993	
	Ankle	preferred	4.19	(2.60)	9.75	(1.19)	14.66	(2.36)	0.123		0.171	
		maximum	8.92	(1.91)	11.84	(0.85)	10.53	(1.84)	0.338		0.801	

SE standard error

* adjusted for height, weight, sex, gait speed for all, except gait speed, which did not include speed adjustment

† significant difference was disappeared after adjusting with maximum concentric knee strength (in angular velocity $180^\circ/\text{sec}$)

§ significant difference was disappeared after adjusting with maximum eccentric knee strength (in angular velocity $30^\circ/\text{sec}$)