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Step Length Reductions in Advanced Age: The Role of Ankle and Hip Kinetics

James Oat Judge,[1] Roy B. Davis, III,[2] and Sylvia Õunpuu[2]

[1]Travelers Center on Aging, University of Connecticut Health Center.
[2]Gait Laboratory, Newington Children's Hospital, Newington, Connecticut.

Background. Aging is associated with a reduction in gait velocity, which is due to a shortened step length. This study investigated the relationship between joint kinetics and step length.

Methods. Three-dimensional gait kinematics and kinetics were measured during usual pace gait in 26 older subjects (average age 79) and in 32 young subjects (average age 26). Gait measures were obtained at maximal velocity in five older subjects. Lower extremity strength was measured in the older subjects on an isokinetic dynamometer.

Results. Older persons had a 10% shorter step length during usual gait, when corrected for leg length (.65 ± .07, .74 ± .04/leg length, respectively, $p < .001$). Older persons had reduced ankle plantarflexion during late stance (13 ± 5°, 17 ± 5°, $p = .02$) and lower ankle plantarflexor power (2.9 ± 0.9 W kg^{-1}, 3.5 ± 0.9 W kg^{-1}, respectively, $p = .007$). Ankle strength was associated with plantarflexor power developed during late stance ($r = .49$, $p < .001$). When gait kinetics were corrected for step length, the older subjects developed 16% greater hip flexor power during late stance than younger subjects (estimate of effect: .15 W kg^{-1}, $p = .002$). Older subjects were unable to increase ankle plantarflexor power at maximal pace, but increased hip flexor power 72% (1.1 ± 0.3 W kg^{-1} to 1.9 ± 1.0 W kg^{-1}, $p = .02$).

Conclusions. Older subjects had lower ankle plantarflexor power during the late stance phase of gait and appeared to compensate for reductions in plantarflexor power by increasing hip flexor power. Appropriate training of ankle plantarflexor muscles may be important in maintaining step length in advanced age.

WALKING is an integral component of many tasks required for independent living. Slow gait is strongly associated with dependence in instrumental activities of daily living (1) and was one component of a performance scale (with chair rise time and standing balance) that increased the risk of loss of mobility, transfer to a nursing home, or death (2,3). Gait velocity and qualitative measures of gait (symmetry of step length, arm swing, path deviation, trunk sway, foot clearance, or shuffling gait) predict functional status and fall risk in older persons (4–6).

Gait velocity is maintained through adult life until the seventh decade; thereafter, usual gait velocity declines 12–16% per decade and maximal velocity declines about 20% per decade (7–10). Two consistent findings have been reported in studies of older subjects. Older persons have a reduced stride length (8–11), spend more time with both feet on the ground (double support), and less time with one foot on the ground (single support) (8). Stance time (proportion of gait cycle with the foot on the ground) increases in men from 59% in 20-year-olds to 63% in 70-year-olds, which increases double support time from 18% to 26% (8). Cadence (steps min^{-1}) is usually unchanged with advanced age (7–9). Murray and others have described kinematic changes associated with a shorter step length: reduced pelvic rotation, hip flexion/extension, and ankle plantarflexion (8,11).

However, it is difficult to determine from cross-sectional studies which describe gait changes why step length is reduced and double support time is increased. Two alternate explanations have been advanced to explain age-associated changes in gait-muscle weakness and impaired balance (12,13). If balance, which we conceptualize as the ability to control the center of mass (COM) during movement, is impaired, older persons may reduce single support time to reduce subjective instability. Alternatively, muscle weakness may reduce power developed during early stance (hip extension), or late stance (ankle plantarflexion, and hip flexion), which will reduce velocity and shorten the step length. Muscle strength is positively correlated with gait velocity and step length in older persons (9,14–16). Knee extension strength (15) and ankle plantarflexion strength (16) are associated with gait velocity. In middle-aged subjects with polio, ankle plantarflexor strength was the only strength measure that was an independent predictor of gait velocity (17). Balance is also associated with gait velocity (18).

The major purpose of this report was to determine if hip extension or ankle plantarflexion power was primarily responsible for the shorter step length in older persons. An earlier study found that ankle plantarflexor work was 34% lower in older subjects compared to young subjects, but hip extensor and flexor work were similar in both groups (12). The second purpose of this report was to determine if quadriceps strength and knee kinetics were responsible for the shortened step length in older subjects. We hypothesized that older persons with quadriceps weakness might reduce their gait velocity to limit knee flexion during early stance.

METHODS

Older subjects. — The recruitment strategy was designed to enroll relatively healthy, nonathletic older persons, recruiting from senior centers and three elderly housing sites. Inclusion criteria were age greater than 70 years, ability to walk without assistive device for 8 meters, and ability to stand erect with thighs and shanks vertical (anatomical position). Exclusion criteria included history of a stroke or evidence of focal or neurologic deficits; cognitive impairment (score <22 on MMSE) (19); treatment with antidepressants or neuroleptics; unstable angina or recent myocardial infarction; poorly controlled hypertension; symptomatic orthostatic hypotension; hip or knee joint replacement; and inflammatory arthritis.

Young subjects. — The young adult subjects were recruited to develop a healthy adult data base, and the recruitment efforts were separate from the recruitment of the older subjects. This is the first presentation of the data from this data base. Inclusion criteria were age 18 to 42, and good health. Exclusion criteria included lower extremity musculoskeletal complaints; joint replacement or knee joint instability; restriction in passive range of motion of the knee or hip; and history of neurological disease.

Gait analysis. — Gait analysis was performed at Newington Children's Hospital gait laboratory. The methodology has been reported earlier (20,21). To quantify the three-dimensional joint angular changes (kinematics), 20 passive reflective markers aligned with respect to specific bony landmarks were placed on both of the lower extremities, the pelvis and the trunk of the subject. Three-dimensional bilateral trajectories of the markers were monitored by an optically based motion measurement system (VICON, Oxford Metrics, Oxford, England) while the subject walked along an 11-meter walkway. Data were acquired in a measurement space from 3 to 8 meters along the walkway. The lower extremity and pelvic kinematics were determined from the marker and estimated joint center displacement data using Euler's angles (23). Joint moment and power (kinetic) results were calculated by combining marker/joint center locations, anthropometric estimates of segment mass and mass moments of inertia, and ground reaction force data acquired with three force platforms (AMTI, Newton, MA) through Newtonian mechanics, i.e., Newton's second law and Euler's equation of motion (22). Temporal and stride parameters were also computed from the marker displacement data. To permit temporal comparisons across subjects with different cadences, all temporal variables are reported as percentages of one complete gait cycle (% GC). The gait cycle begins at initial foot contact (0% GC) and continues through stance phase (0 to about 60% GC) swing (about 60% to 99% of GC).

Subjects performed at least three trials for each limb. All trials were assessed for comparability of joint kinematics and kinetics. The Intraclass Correlation Coefficient for 6 trials (both sides) for all variables exceeded .80. For all analyses, the data from the first trial for each side were used. Five older subjects also walked at their maximal pace. Subjects were instructed to walk "as fast as you can walk without running or without feeling that you will trip or fall."

Muscle strength/passive range of motion. — Strength and joint range of motion measures were obtained from the older subjects only. Peak joint moment during isokinetic movements were obtained on a Cybex 340 isokinetic dynamometer on the right limb at 60° s^{-1} at the hip, knee, and ankle during flexion and extension. Ankle plantar/dorsiflexion was performed in the supine position, with the knee in full extension. Hip extension/flexion was performed in the supine position. Subjects practiced 4 warm-up movements and then performed 4 maximal movements. Results are the net moment about the axis of the dynamometer, without limb weight correction. Results are corrected for body mass, and reported either as moment (N•m kg^{-1}) or power (W kg^{-1}). Passive range of motion (ROM) data were recorded in increments of 5°. Ankle ROM was obtained with the knee flexed at 90° and in full extension. Hip range of motion in internal and external rotation was measured in the prone position with the knee flexed at 90°.

Statistical analysis. — Statistical analysis was performed using SPSS 6.1 for Windows. Variables reported are the average of the left and right sides. Repeated measures analysis of variance (ANOVA) tested for age group (between subject) and laterality effect (left and right within subject), and in a separate model for pace effect (within subject) on the kinematic and kinetic measures. Parameter estimates (with 95% CI) are reported. As laterality effect was found for only one variable, it is not reported in the tables. Multivariate analysis of covariance (MANCOVA) models tested for age-group differences in kinetic variables, using step lengths of the left and right steps as covariates. Multivariable linear regression estimated the contribution of joint power to step length, using a stepwise entry procedure ($p = .05$ to enter, $p = .10$ to remain). Bivariate correlations tested the relationship between muscle strength and step length and joint kinetics.

RESULTS

Subjects. — The mean age of the older subjects was 79 years (range 70–90), and the mean age of the young subjects was 26 years (range 18–42) (Table 1). Older subjects had an average of 14 years of education. The older subjects were fairly active: 52% walked nearly every day; 57% climbed stairs daily; and 22% performed endurance activities (walking or other activity for >15 minutes) more than once a week. Nine older subjects reported slight or moderate knee pain or stiffness, and three subjects reported hip joint pain or stiffness. The kinematic and kinetic results were not significantly different in the subjects with joint symptoms compared to those without joint symptoms.

Passive ROM in ankle dorsiflexion of the older subjects averaged 2 ± 3° when tested with the knee in full extension, and 11° ± 50° with the knee flexed to 90°; ankle plantarflexion averaged 30° ± 6°. Hip ROM in internal and external rotation averaged 32 ± 12° and 32 ± 9°, respectively.

Older subjects were similar in body mass and leg length but were 8 cm shorter in height (Table 1). Older subjects walked at a lower velocity than younger subjects (103 cm s^{-1} compared to 116 cm s^{-1}), but older subjects had a faster cadence than younger subjects (116 steps min^{-1} compared to 110 steps min^{-1}). Step length averaged .65 of leg length in the older subjects, which was significantly shorter compared to the .74 leg length in young adults. Single support time was 37% in the older subjects and 40% in the younger subjects. This means that, on average, the toe off of the opposite foot occurred at 13% GC in the older subjects and at 10% of GC in the younger subjects.

Usual pace kinematics. — Figure 1 depicts the grand mean kinematics for all subjects in each age group in the sagittal, frontal, and transverse planes. The left column is frontal or coronal plane, the middle column is the sagittal plane, and the right column is the view from the ceiling (transverse plane). Table 1 lists selected kinematic mea-

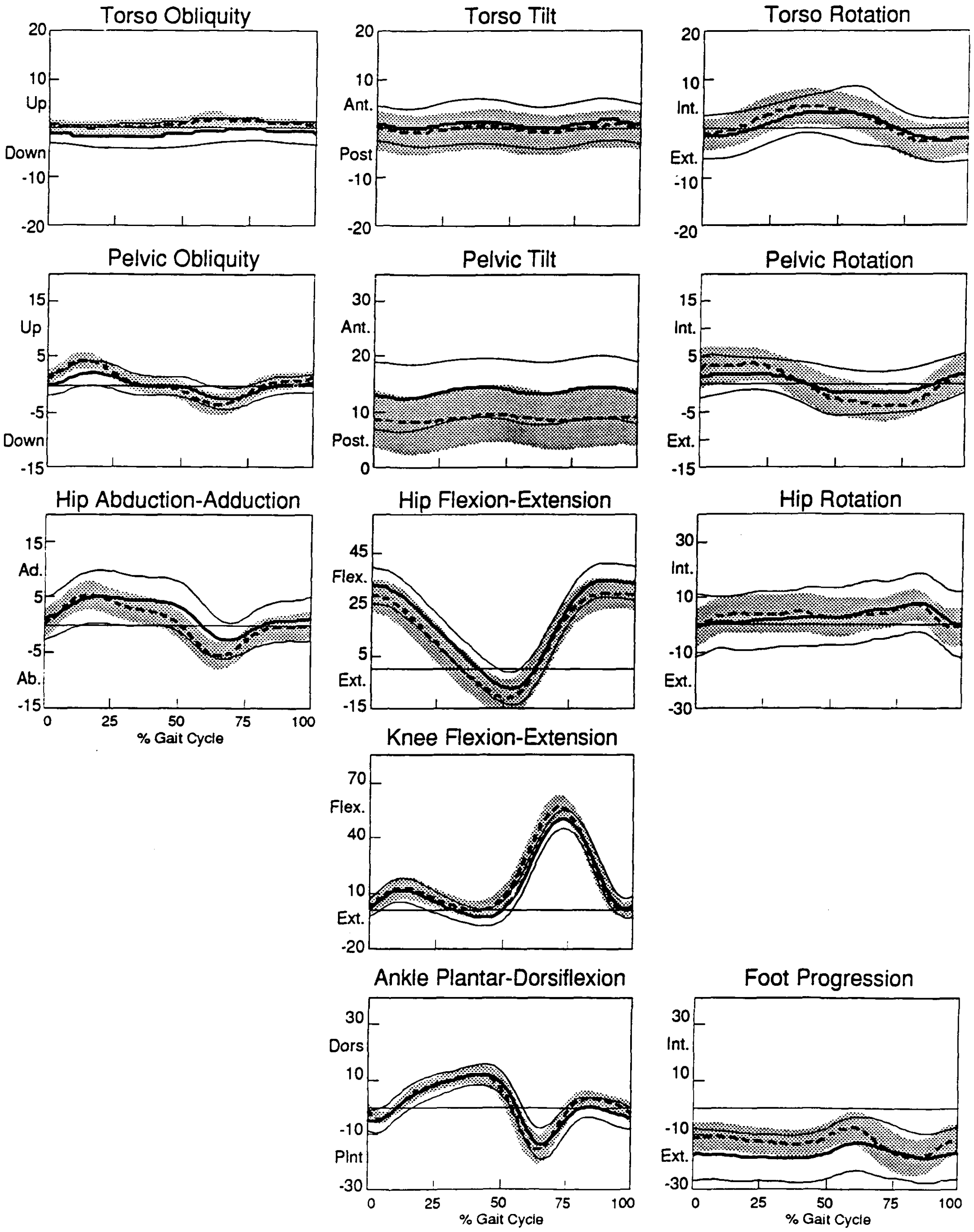

Figure 1. Gait kinematics of young and older subjects. The ordinate for all subsequent graphs is a complete gait cycle (GC), or stride, where 0% represents initial foot contact, and 100% initial foot contact of the next stride. The stance phase is from 0–60% GC in the younger subjects and 0–63% in the older subjects. The left column represents kinematics in the frontal (coronal) plane, the middle column the sagittal plane, and the right column the transverse plane (view from the ceiling). For both age groups, the mean and one standard deviation above and below the mean is graphed. For younger subjects the mean value is the thick dotted line, and the shaded area is ± 1 *SD*. For older subjects, the mean value is the thick solid line, and the thin solid lines are ± 1 *SD*.

Table 1. Subject Characteristics and Kinematic Measures

Measure	Young Adults $n = 32$	Older Adults $n = 26$	Age Group ANOVA (p-value)	Age Group Effect (95% CI)
Age	26 ± 6	79 ± 6		
Body mass (kg)	64.9 ± 11.6	65.7 ± 11.7	.79	
Height (cm)	166 ± 10	158 ± 9	.005	3.4 (1.2, 6.5)
Leg length (cm)	86 ± 6	84 ± 5	.34	
Gait velocity ($m\ s^{-1}$)	1.16 ± .13	1.03 ± .13	<.001	.09 (.03, .14)
Step length (proportion of leg length)	.74 ± .04	.65 ± .07	<.001	.06 (.04, .08)
Single support time (proportion of gait cycle)	40 ± 2	37 ± 3	<.001	2.0 (1.1, 3.0)
Cadence (steps min^{-1})	110 ± 9	116 ± 7	.02	3.6 (0.6, 6.6)
Kinematics				
Foot/ankle				
Foot angle ("toe out")	11 ± 4°	16 ± 5°	<.001	4.1° (2.5°, 5.7°)
Ankle angle at initial contact	−3 ± 3°	−4 ± 4°	.01	
Peak dorsiflexion	12 ± 3°	13 ± 3°	.44	
Peak plantarflexion	−17 ± 5°	−13 ± 5°	.002	2.9° (1.1°, 4.7°)
Knee				
Loading response (flexion)	12 ± 6°	12 ± 7°	.99	
Peak knee extension	−1 ± 5°	−3 ± 5°	.06	1.6° (0°, 3.4°)
ROM – sagittal plane	59 ± 5°	55 ± 5°	<.001	2.9° (1.3°, 4.5°)
Hip				
Hip flexion (initial contact)	30 ± 6°	33 ± 7°	.11	
Peak hip extension (stance)	−11 ± 7°	−8 ± 7°	.12	
ROM – sagittal plane	42 ± 3°	43 ± 5°	.58	
Hip abduction at toe off	6 ± 2°	2 ± 3°	<.001	3.2° (2.2°, 4.2°)
Pelvis/torso				
ROM – sagittal	3 ± 1°	3 ± 1°	.62	
ROM – transverse	9 ± 4°	7 ± 2°	.002	1.7° (0.6°, 2.8°)
ROM – frontal	9 ± 3°	6 ± 2°	<.001	2.3° (1.3°, 3.4°)
Pelvic tilt (anterior)	10° ± 5°	14° ± 6°	.01	2.7° (.7°, 4.7°)
Trunk tilt	−1° ± 4°	0° ± 4°	.69	

sures. Two types of differences between old and young subjects were found: (a) upward or downward shifts of the joint angle or body orientation throughout the entire cycle (differences in posture); and (b) differences in joint motion limited to specific portions of the gait cycle.

Postural differences. — Older subjects walked with a 4° greater anterior (downward) tilt of the pelvis, but there was no difference in the angle of the torso relative to vertical. The hip kinematics in the older subjects were shifted 3° to greater flexion compared to the younger subjects, but hip ROM did not differ between age groups. The combination of a 4° anterior pelvic tilt and 3° hip flexion bias in older persons means that the movement of the thigh relative to vertical was similar in young and old subjects. There were no significant differences in hip rotation. The other notable finding was that older subjects had 5° greater external rotation of the foot during stance.

Kinematic differences. — Older subjects had reduced motion at the pelvis in the frontal and transverse plane, as well as prolonged hip adduction during stance phase. Pelvic rotation in the transverse and frontal planes was 3° lower in older subjects. Older subjects had greater peak knee extension during stance −3° ± 5° (hyper extension) compared to young subjects (−1° ± 5°), and lower knee motion than younger subjects (55° ± 5°, 59° ± 5°, respectively). Older subjects also had a significantly reduced ankle plantarflexion during late stance (13° ± 5°) compared to young subjects (17° ± 5°). Peak ankle dorsiflexion angle did not differ by age group. The peak dorsiflexion during stance in the older subjects averaged 12°, which was much greater than the maximal dorsiflexion measured in passive ROM (2° ± 3°).

Kinetics. — The only significant difference in joint power between old and young subjects was in peak ankle plantarflexor power (Figure 2, Table 2). Older subjects developed 17% lower power than young subjects (2.9 ± 0.9 W kg^{-1}, 3.5 ± 0.9 W kg^{-1}, respectively). The estimated age-group effect was .44 W kg^{-1} (95% CI .12, .76 W kg^{-1}). Most of the other kinetic measures tended to be higher in the younger subjects, but the differences were not statistically significant. For example, peak knee power absorption during K3 (at 58% GC) was slightly (9%) lower in older subjects, but this difference was not significant ($p = .21$). Likewise, the negative work (power absorption) during K3 (which represents the integration of knee power during K3) was slightly, but not significantly, lower in older subjects.

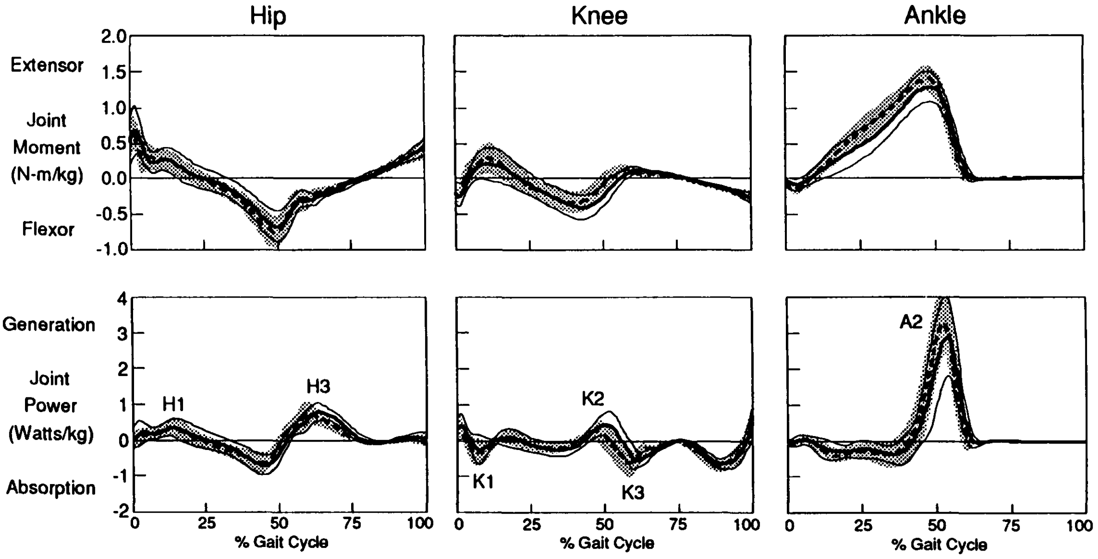

Figure 2. Saggital plane kinetics. The top row represents joint moment, corrected for body mass. The bottom row represents joint power. The horizontal line (0) differentiates power absorption (negative values) and power generation (positive values). For younger subjects, the mean value is the thick solid line, and the shaded area is ± 1 *SD*. For older subjects, the mean value is the thick dotted line, and the thin solid lines are ± 1 *SD*.

Table 2. Gait Kinetics

Joint Power (Watts kg^{-1})	Young	Older	MANOVA *p*-value	MANOVA Age Effect Estimate (95% CI)	MANCOVA* Correct for Step Length *p*-value	MANCOVA* Correct for Step Length Age Effect Estimate (95% CI)
Ankle plantarflexion	3.5 ± .9	2.9 ± .9	.007	.44 (.012–.76)	.17	
K1 (loading response)	–.33 ± .32	–.22 ± .32	.17		.90	
K2 (mid stance)	.16 ± .13	.17 ± .19	.87		.14	
K3 (late stance)	–.77 ± .25	–.70 ± .21	.21		.17	
K3 (Work – J kg^{-1})	–.066 ± .029	–.056 ± .020	.16		.88	
Hip extension	.55 ± .24	.47 ± .26	.17		.80	
Hip flexion	–.87 ± .29	–.92 ± .27	.45		.002	–.15 (–.04, –.26)

Note: Negative values represent power (or work) absorbed at the joint, positive values represent power generated at the joint.
*MANCOVA = Multivariate analysis of covariance.

In contrast, hip flexor power (at 60% GC) was slightly higher in older subjects compared to young subjects (.92 ± .27 W kg^{-1}, .87 ± .29 W kg^{-1}, respectively). When the analysis was adjusted for differences in step length, older subjects developed 16% more hip flexor power (effect .15 W kg^{-1}, p = .002) than younger subjects. There were no age-group differences for any other joint power variable, after adjusting for step length.

Predictors of step length. — Two multivariable linear regression models tested the contribution of peak joint power to step length (Table 3). The first model included all joint power variables as independent variables, and the second model added age group as an independent variable. Ankle plantarflexor power, hip extensor power, and hip flexor power were independent predictors of step length in Model 1; joint power explained 62% of the variance in step length. Ankle power was the strongest predictor of step length, explaining 52% of the variance in step length. Model 2, which included age group, explained 70% of the variance in step length, and the standard error of the estimate was reduced about 10% by the addition of age group. Ankle plantarflexor and hip extensor power were independent predictors of step length, but hip flexor power was no longer in the model. The older group had a step length which was 4.6 cm shorter (Beta –.055 multiplied by leg length), after correction for joint power.

To test if muscle weakness was related to step length in older subjects, bivariate comparisons of isokinetic muscle strength and gait measures were performed (Table 4). Knee and ankle strength was associated with step length and joint power developed during gait, but there was no significant relationship between hip flexion or extension strength and step length or power developed at the hip (Table 4). Isokinetic knee extension strength was correlated with the power absorbed at the knee during the loading response (K1, r = –.55, p = .004), power generated in knee extension during stance (K2, r = .64, p = .001), but not power

Table 3. Gait Kinetics-Multivariate Predictors of Step Length

	Kinetic Model $R^2 = .62$, *SEE* = .044			Kinetic Model With Age Group $R^2 = .70$, *SEE* = .04		
Joint Power (Watts kg^{-1})	Beta	Partial R^2	*p*-value	Beta	Partial R^2	*p*-value
Ankle plantarflexion	.066	.52	>.001	.046	.52	>.001
K1–Knee extensor (loading response–absorption)	.151		.08	–.14		.06
K2 (mid stance–generation)	.087		.31	.11		.15
K3 (late stance–absorption)	–.118		.33	.098		.22
Hip extension	.111	.06	.003	.068	.04	.007
Hip flexion	–.076	.04	.01	–.103		.29
Age group				–.055	.15	>.001

Table 4. Lower Extremity Strength and Bi-variate Relationships Between Isokinetic Strength Measures, Joint Kinetics and Step Length in Older Adults

Joint Kinetics-Gait (power W kg^{-1})	Isokinetic Strength Measures			
	Ankle Plantarflexion	Knee Extension	Hip Extension	Hip Flexion
Ankle plantarflexion	.57 (.003)	.54 (.006)		
K1–knee absorption		–.55 (.004)		
K2		.64 (.001)		
K3				
Hip extension				
Hip flexion				
Step length	.38 (.006)	.69 (<.001)		
Isokinetic strength Mean ± 1 *SD* (N•m kg^{-1})	.76 ± .23	1.22 ± .32	1.28 ± .36	.72 ± .24

Notes: Only significant relationships are listed ($p < .01$). Pearson *p*-values are listed in parentheses.

absorbed during late stance (K3). Isokinetic strength of the ankle plantarflexors was associated with ankle plantarflexor power developed in late stance ($r = .57, p = .003$) and with step length.

Comparison of usual and fast gait in older subjects. — To help determine the limiting factors in step length in older persons, five subjects had additional trials at maximal gait velocity. There were substantial differences in most of the gait parameters. Velocity increased 26% from usual to maximal pace (from 112 ± 17 to 142 ± 36 cm s^{-1}); cadence increased 15% (from 117 ± 7 to 134 ± 9 steps min^{-1}), and step length increased 10% (from .67 ± .10 to .74 ± .09 leg lengths). Single support (as a proportion of the gait cycle) did not increase (39 ± 4% to 40 ± 4%) (Figure 3, Table 5).

The most striking changes in kinematic and kinetic measures from usual to maximal gait occurred at the hip. Hip flexor moment increased 25%, and hip flexor power increased 72% at maximal gait ($p < .05$). Hip extension moment and power values were 44% and 57% higher at maximal pace, respectively, but these differences were not statistically significant. Knee kinetics were notable for greater variability at maximal pace, and a 36% increase in peak power absorption during late stance ($p = .007$). In contrast, ankle power and ankle moment did not increase from usual to maximal gait. Ankle plantarflexor moment was unchanged at 1.4 ± 0.3 N•m kg^{-1}. The kinematics graph demonstrates that plantarflexion began earlier in the gait cycle at maximal pace, but there was no increase in peak dorsiflexion or plantarflexion range of motion.

DISCUSSION

Older subjects had significant differences in peak ankle flexor and hip flexor power compared to young subjects. The data from this study support the hypothesis that ankle plantarflexor power is the primary kinetic factor responsible for short step length in older subjects. The analyses in the present study extend the findings of earlier studies which found diminished ankle power during usual gait, and found associations between ankle strength and gait velocity (12,16).

Kinetics. — In this study, older persons generated significantly lower ankle plantarflexor power than young subjects, and ankle plantarflexor power was by far the strongest predictor of step length in the multivariable linear regression models. The prediction of step length by ankle strength was unaffected by the addition of age group into the model. Further evidence for the importance of ankle plantarflexor function was found in the strong relationship between isokinetic ankle plantarflexor strength and ankle plantarflexor power developed during late stance.

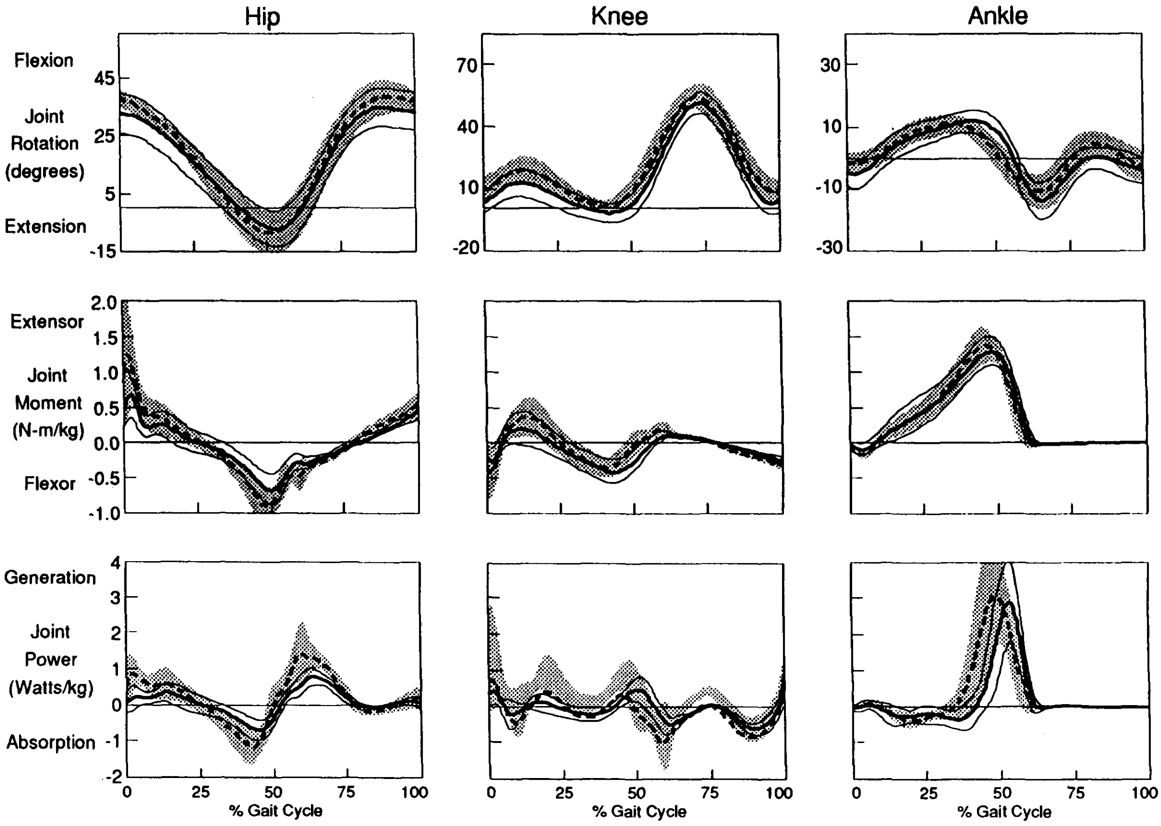

Figure 3. Older subjects — sagittal plane kinematics and kinetics at usual and maximal pace. Usual pace: mean value is thick solid line, the thin solid lines are ± 1 *SD*. Maximal pace: the mean value is the thick dotted line, and shaded area is ± 1 *SD* ($N = 5$).

Table 5. Kinetics — Usual and Maximal Pace in Older Subjects

	Usual	Maximal	ANOVA *p*-value	Estimate of Effect of Pace (95% CI)
Power (W kg^{-1})				
Ankle plantarflexion	3.1 ± 1.2	3.2 ± 1.5	.16	
K1 (loading response)	−.25 ± .27	−.50 ± .28	.19	
K2 (mid stance)	.30 ± .24	.47 ± .41	.25	
K3 (late stance)	−.89 ± .43	−1.21 ± .68	.03	−.30 (.03, −.57)
K3 Work (J kg^{-1})	−.70 ± .03	.11 ± .04	.007	−.03 (−.01, −.05)
Hip extension	.70 ± .30	1.1 ± .50	.14	
Hip flexion	1.1 ± .30	1.9 ± 1.0	.02	.57 (.13, 1.0)
Joint moment (N• m kg^{-1})				
Ankle plantarflexion	1.4 ± .30	1.4 ± .20	.48	
Hip extension	.90 ± .40	1.3 ± .80	.21	
Hip flexion	−.80 ± .20	−1.0 ± .30	.005	−.20 (−.11, −.31)

Notes: $N = 5$. For power variables, negative values represent power absorbed at the joint, positive values represent power generated at the joint.

The maximal pace gait data on five older subjects also support the importance of ankle plantarflexor function as a potential limiting factor in gait. While step length increased 10% and cadence increased 15%, older subjects were unable to increase their ankle plantarflexor power. This suggests that older persons at usual pace are generating near maximal plantarflexor power. Although the present study did not obtain kinetic measures at maximal gait in young subjects, in an earlier study, young adults increased ankle plantarflexor power 38% (3.4 W kg^{-1} to 4.7 W kg^{-1}) at maximum pace (12), while the older subjects in the present study increased ankle power only from 3.1 W kg^{-1} to 3.2 W kg^{-1}. However, the small number of subjects tested at both usual and maximal pace severely limit the inferences to be drawn. Testing of a larger group of older subjects is needed to provide confidence in the ankle power findings noted in this small subset of older subjects.

Three potential roles of ankle plantarflexor kinetics on body motion have been proposed: (a) to allow the body to advance over the stance foot; (b) to initiate the movement of the stance leg into swing; and (c) to propel the body forward. To accomplish the first proposed role, ankle plantarflexors contract eccentrically during mid-stance (from 20–45% GC) while the center of mass is moving forward and ahead of the stance leg (12,20). Support for this proposed role of ankle plantarflexors is found in a study of healthy young adults after posterior tibial nerve block of the left, which paralyzed the ankle and toe flexors and anesthetized the plantar surface of the foot (23). Single stance time on the left leg was reduced, the progression of the center of force over the left foot was markedly reduced, and the *right* step length was markedly shortened.

The second and third postulated roles for ankle plantarflexors are more controversial. Ankle plantarflexors contract concentrically in late stance (45–60% GC) and may work in coordination with hip flexors to accelerate the shank and thigh forward and upward into swing. Some texts have argued that ankle plantarflexors primarily act to propel the body forward (12,24). However, convincing data on the role of the plantarflexors in late stance has not been presented.

The data from the present study are consistent with ankle plantarflexors contributing to accelerate the stance leg into swing. Older subjects generated greater hip flexor power than expected for their step length, compared to young subjects. The finding of increases in hip flexor power in late stance and lower ankle plantarflexor power in older subjects suggests that older persons were substituting hip flexor power to compensate for reduced ankle plantarflexor weakness. Further evidence for substitution of hip flexor power for weak ankle plantarflexor power is found in a study of diabetics with peripheral neuropathy and plantarflexor weakness. Diabetic subjects with marked plantarflexor weakness developed greater hip flexor power during late stance, but statistical analysis was not performed (25,26).

The data from this study also support the third proposed role of ankle plantarflexors — to accelerate the body forward, but the argument is only inferential. Ankle plantarflexor power was the only kinetic variable that was significantly diminished in older subjects. If the ankle plantarflexors played only a minor role in advancing the body, the role of the hip extensors would necessarily be prominent. The absence of significant reduction in hip extension power, combined with the small contribution of hip extensor power ($r^2 = .06$) relative to the large contribution of ankle plantarflexor power ($r^2 = .52$) to the multivariable linear regression for step length supports an important role of ankle plantarflexor power to propel the body forward.

Knee kinetics and muscle strength. — This study found no direct evidence that knee kinetics play a limiting role in step length in older subjects. Knee flexion during the loading response was identical (12°) in both age groups. The power absorbed by the knee at K1 tended to be lower ($p = .17$) in older subjects at usual pace, but K1 power tended to increase from usual to maximal pace in older subjects, suggesting that older subjects were willing and able to increase power absorption at the knee. Therefore, we do not think that older subjects reduced step length and gait velocity to avoid the potential instability of knee flexion during the loading response. However, the strength of the bivariate correlations between knee extension strength and knee joint kinetics and step length is puzzling.

The knee joint kinetic curves (Figure 2) are notable for low joint moments and power, and EMG recordings demonstrate low quadriceps activity during gait, except during the loading response (27). Despite this, knee extension strength had the strongest association with step length ($r = .69$) of all six lower extremity strength measures. Knee extension strength was associated with power developed and absorbed at the knee during the loading response (K1), and power developed during midstance (K2), as well as power developed at the ankle. The average isokinetic knee extension power was 8 times greater than the maximum knee extensor power developed during gait (1.28 W kg^{-1} isokinetic power, and .16 W kg^{-1} during K2), and more than 5 times greater than the maximal power absorption during K1. It is possible that knee extension strength, representing the largest muscle group in the lower extremity, may be the best measure of overall leg strength. The difference between the strong correlation between knee extension strength and step length and the absence of a correlation between isokinetic hip strength and step length may be primarily due to limitations in isokinetic strength measures, and does not reflect the relative importance of power developed by the quadriceps compared to hip extensors and flexors during gait. For example, isokinetic hip extension does not include the potential contribution of a two-joint muscle (hamstrings) to hip extension moment.

Modeling the kinetics of late stance. — The joint power figures in the bottom row of Figure 2 illustrate the sequential power generation during late stance beginning at the ankle (peak power at 51% of GC), followed by power absorbed at the knee, K3 (peak at 58% GC), and finally hip flexion power (peak at 60% GC). The power generation moves from the distal (foot/ankle) to the proximal joints. The flexion of the knee is accomplished with little muscle activity of the knee extensors or flexors (27). In the present study, older subjects had lower peak K3 power absorption than younger subjects. In an earlier study, Winter (12) reported that older subjects had much greater work done at the knee during K3 than young subjects (−.89 J kg^{-1} and −.49 J kg^{-1}, respectively). The authors interpreted their results as evidence that the knee flexion absorption of energy reduced the energy transferred to the body by the ankle plantarflexors. Our data and our interpretation of the results differ from Winter. We interpret K3 as the natural consequence of the transfer of energy generated by the ankle plantarflexors to the knee, which flexes the knee. Knee flexion in early swing is also for foot clearance to prevent a trip during swing.

Limitations. — Two study design issues limit the interpretation of the results. A cross-sectional study cannot determine causality. While several statistical strategies were used to gain an insight into the possible limiting factors for step length, only a longitudinal study or an intervention trial can determine the reason for step length declines. Determining the role of joint power and moment play in the motion of the body during gait will probably require new or refined analytic techniques. The present study provides data that are consistent with models of joint power and resultant body motion, but the analytic strategies used here cannot determine if these models are correct. Several strategies which have been used in the analysis of jumping and running may be appropriate for the analysis of the transfer of energy across limb and body segments, and may advance our understanding of the effects of joint power on body motion (28).

Also, the absence of quantitative balance data prevented our determining the role that balance plays in the maintenance of step length, and of the interaction between balance and muscle strength. In an earlier study by this lab, balance performance during challenging platform tilts was associated both with lower extremity strength and gait velocity (1). Determining which test of balance is most relevant to stability during walking has not been determined, but the functional base of support (29), which measures sagittal plane control, and tandem stance (3) and single stance, which measure frontal plane control, may be useful because they are similar to the motor control tasks during single support.

Clinical implications. — Ankle plantarflexion strength and power in older persons appear to be important to maintain step length. Regardless of the relative importance of the different actions of the plantarflexors — to stabilize the body during single support, propel the body forward, and to accelerate the stance leg into swing — increasing ankle plantarflexor strength and power are likely to increase step length.

Training studies in frail older persons have found that either strength training alone (knee extension and flexion, and sitting leg press exercise, which trains hip extension, knee extension, and ankle plantarflexion), or strength training (knee and hip extension, ankle dorsiflexion) combined with simple balance exercises, can increase gait velocity in frail subjects (30,31). Balance training or resistance training in the healthy elderly, including one study that trained plantarflexors, did not improve gait velocity (32,33). In contrast, a sequential study of resistance training followed by endurance training (brisk walking) found no improvement in gait velocity following the initial resistance training component, despite improving isokinetic plantarflexor strength. However, gait velocity improved following the endurance training component (34). The data from the present study and intervention trials suggest that new approaches to train the gastrocnemius/soleus and toe flexors to improve gait should be explored. Regular walking may be the best primary prevention strategy to maintain step length, but the best strategy to improve step length has not been determined.

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Address correspondence to Dr. James Oat Judge, University of Connecticut Health Center, Travelers Center on Aging, MC-5215, Farmington, CT 06030-5215. E-mail: judge@nsol.uchc.edu

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