ORIGINAL ARTICLE

The Effect of Walking Speed on Lower-Extremity Joint Powers Among Elderly Adults Who Exhibit Low Physical Performance

Adam Graf, MS, James O. Judge, MD, Sylvia Õunpuu, MS, Darryl G. Thelen, PhD

ABSTRACT. Graf A, Judge JO, Õunpuu S, Thelen DG. The effect of walking speed on lower-extremity joint powers among elderly adults who exhibit low physical performance. Arch Phys Med Rehabil 2005;86:2177-83.

Objectives: To compare peak joint powers and joint angles between comfortable and fast walking speeds among a group of elderly adults who exhibit low physical performance, and to test the primary hypothesis that peak ankle powers would not change when walking speed was increased, but that peak hip power output would increase significantly with speed.

Design: Three-dimensional analysis of joint kinematics and kinetics during comfortable and fast walking by both healthy and low-performing elderly adults (age, >70y).

Setting: Gait laboratory.

Participants: Twenty-four healthy elderly adults and 27 elders who exhibited low performance on a standard battery of walking, standing balance, and chair-rise tasks that places them at risk of mobility-related disability.

Interventions: Not applicable.

Main Outcome Measures: Peak lower-extremity joint powers and joint angles.

Results: Low-performing elders increased both ankle and hip power outputs to increase walking speed. However, peak ankle power remained significantly below that of the healthy elderly adults even when the low-performing elders walked at a faster gait speed. Joint-power changes in the low-performing elderly were accompanied by a reduction in hip extension and ankle dorsiflexion, and an increase in transverse pelvic rotation.

Conclusions: Compared with healthy elderly, the low-performing elderly adults showed speed-independent differences in ankle and hip mechanics that may reflect underlying neuromuscular impairments. In particular, an understanding of the interdependent contributions of hip flexibility and ankle power limitations seem important to inform interventions to maintain gait into advanced age.

Key Words: Aged; Ankle; Biomechanics; Hip; Rehabilitation; Walking.

From the Departments of Biomedical Engineering (Graf, Thelen) and Mechanical Engineering (Thelen), University of Wisconsin-Madison, Madison, WI; Division of Geriatrics, University of Connecticut, Farmington, CT (Judge); and Center for Motion Analysis, Connecticut Children's Medical Center, Hartford, CT (Õunpuu).

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Reprint requests to Darryl G. Thelen, PhD, Dept of Mechanical Engineering, University of Wisconsin-Madison, 1513 University Ave, Madison, WI 53706, e-mail: *thelen@engr.wisc.edu.*

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GAIT IMPAIRMENTS AMONG elderly adults are correlated with loss of physical function, admission to nursing homes, and increased risk of falling.[1,2] Thus, the maintenance of gait is an integral component of interventions aimed at maintaining mobility and independence. Therefore, an understanding of the specific neuromuscular factors that alter gait is important to develop and evaluate effective interventions for those at greatest risk of disability.

Reductions in muscle strength and power capacity may contribute to age-related changes in gait. In particular, ankle plantarflexors generate significant power during normal gait,[3,4] such that impairments to these muscles could induce changes in the coordination of walking. Indeed, ankle muscle power capacity decreases significantly with age, with healthy elders showing power reductions of 20% to 40% relative to young adults.[5,6] These decrements may contribute to the most consistently observed kinetic change in elderly gait, which is reduced ankle power generation during late stance.[4,7-9] Evidence in support of this relation is a high correlation between ankle power output during gait and measures of lower-extremity strength.[7,10] Furthermore, Judge et al[7] found that healthy elderly adults tended to increase hip flexor power rather than ankle plantarflexor power to increase walking speed, suggesting a potential compensatory mechanism for plantarflexor weakness.

McGibbon and Krebs[11,12] showed that elderly adults with physical impairments tend to exhibit even more pronounced reductions in ankle power output during walking. In a related study, they showed that functionally limited elderly generated more energy from the hip and low back as a possible compensation for reduced plantarflexor power ouptut.[13] However, it remains unclear whether the reduced power output, relative to healthy elderly, is actually attributable to limitations in muscle power development or to other reasons such as reduced flexibility.[14,15] Discerning the relative effects of these factors is highly relevant for informing interventions to improve walking performance.

The purpose of the present study was to compare peak joint powers and joint angles between comfortable and fast walking speeds among a group of elderly adults who exhibit reductions in physical performance. We tested our hypothesis that peak ankle powers would not change when impaired elderly increase walking speed, but that peak hip power output would increase significantly with speed. Support for this hypothesis would suggest that ankle power capacity may be saturating and thus may be a limiting impairment in this population. We also compared joint powers and kinematics of the low-performance elderly with a healthy elderly cohort to provide additional data by which to understand the kinematic and kinetic changes that can arise with impairment.

METHODS

Participants

A total of 52 elderly adults, 70 years and older, participated in this study. All subjects were able to walk independently

Table 1: Characteristics of the Healthy and Low-Performance Elders

Characteristics	Healthy	Low Performance
No. of subjects	25	27
Men	8	8
Women	17	19
Age (y)	79±6	76±4
Height (m)	1.59±0.09	1.60±0.12
Body mass (kg)	66.2±11.7	75.9±18.2

NOTE. Values are n or mean ± standard deviation (SD).

without an assistive device. The elderly adults were divided into a group of healthy adults (n=25) and elders who exhibited low performance on a standard physical performance battery (n=27)[15,16] (table 1). All elderly adults were recruited from senior centers or elderly housing sites in the Hartford, CT, area.[17]

Inclusion and exclusion criteria. Exclusion criteria for the healthy adults included the following: recent myocardial infarction, poorly controlled hypertension, history of a stroke, evidence of focal or neurologic deficits, symptomatic orthostatic hypotension, hip or knee joint replacement, and inflammatory arthritis. The healthy adults were fairly active: 52% walked nearly every day, 57% climbed stairs daily, and 22% performed endurance activities (walking or other activity for longer than 15min) more than once a week. A comparison of gait mechanics has previously been made between this healthy elderly cohort and one of healthy young adults.[7]

The adults with low physical performance (hereafter termed low-performance) were recruited to participate in an exercise intervention study that was conducted at the University of Connecticut in conjunction with 3 senior centers.[17] Gait data reported in this study were collected from a subset of intervention study participants on enrollment into the study. All subjects in the low-performance group had mobility impairments as indicated by initially scoring 9 or lower out of 12 (best) on a Short Physical Performance Battery (SPPB) (a test of standing balance, chair rise, and usual gait).[17] Persons scoring at or below 9 on the SPPB are at least 1.6 times more likely to lose activities of daily living (ADL) function and 1.8 times more likely to develop mobility-related disability by a 4-year follow-up than those scoring 10 to 12.[18] However, the low-performance subjects were not home bound and were independent in at least 5 of 6 ADLs (table 2). Additional exclusion criteria for the low-performance group included symptomatic coronary artery disease, poorly controlled hypertension, terminal illness, Parkinson's disease requiring medication, and current enrollment in rehabilitation or an aerobic exercise program.

Table 2: Medical Condition of the Low-Performance Elders

	Chronic Disease Burden						
No.	Mild	Moderate	Self-Health	Falls	JR	PN	A
1	2, 5, 6		Good				
2	2, 3, 5, 8		Good			X	
3	6, 7		Fair				X
4	6		Excellent	X			X
5	2, 3, 5, 6, 7, 8		Good	X	X		
6	2, 5, 6, 7		Good	X			
7	2	5, 11	Good				
8	5	1, 11, 12	Good	X	X		
9	1, 6		Good				X
10	2, 5, 7		Good	X			
11	5, 6		Good				X
12	2	11	Good		X		X
13	2, 5, 6		Good				
14	1, 5		Good				
15		5	Excellent				
16	2, 3		Good				
17	2, 5, 6		Good	X			X
18	2, 3, 4, 5, 7, 8	11	Fair	X	X	X	X
19	2, 5, 6, 8		Good	X			X
20	2, 6	3	Good				
21	2, 5, 7		Fair	X			
22	2, 5, 6, 8		Good	X			X
23	2, 5, 6, 7		Fair	X			
24	2, 6, 7, 8		Good	X			X
25	1, 2, 5, 6		Fair				
26	2, 6		Good				X
27	6	2	Fair				
Total, n (%)				13 (48)	4 (15)	2 (7)	11 (41)

NOTE. Subjects who self-reported a fall in the past year (Falls), a hip or knee joint replacement (JR) replacement, or were diagnosed with peripheral neuropathy (PN) or arthritis (A) are indicated. Chronic disease burden was assessed using the Cumulative Index Rating Scale.[11,26] Legend: 1, cardiac; 2, hypertension; 3, vascular; 4, respiratory; 5, eyes, ear, nose, and throat; 6, musculoskeletal integumentary; 7, neurologic; 8, endocrine metabolic. Mild impairment does not interfere with normal activity; treatment may or may not be required. Moderate impairment interferes with normal activity; treatment is needed.

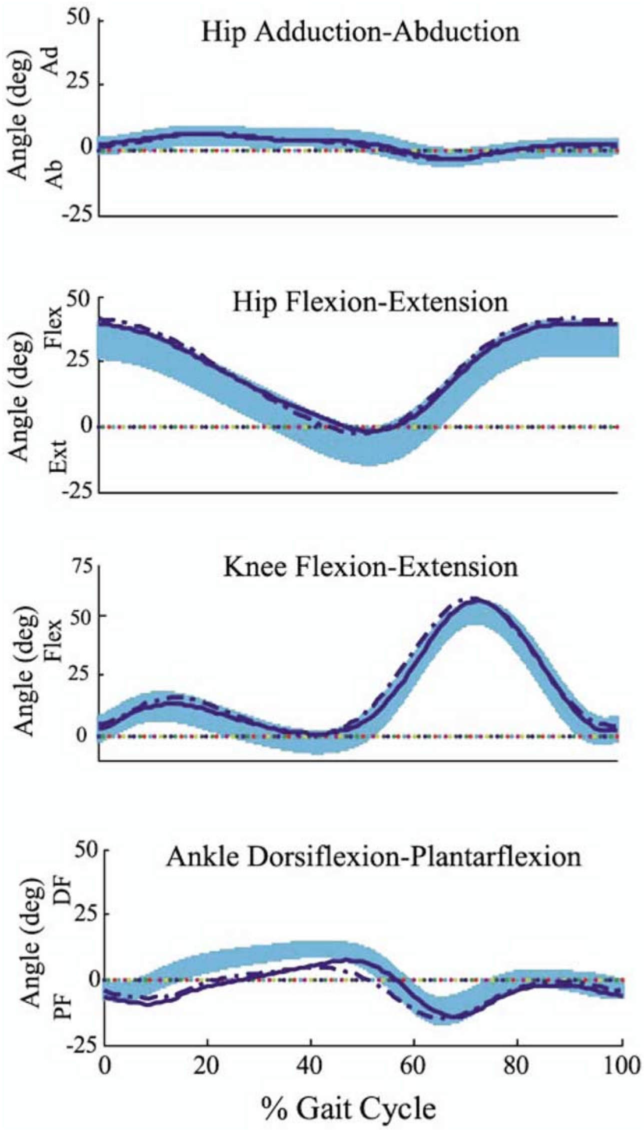

Fig 1. Joint angles throughout the gait cycle for the healthy elderly subjects walking at a comfortable gait (shaded curve representing mean ±1 standard deviation [SD]) and low-performance elderly adults walking at comfortable (solid line) and fast (broken line) gait speeds. Heel strike is at 0% and toe-off is at 62% to 64% of the gait cycle (table 3). Note that the low-performance group exhibits less hip extension during stance, greater hip flexion throughout swing, reduced dorsiflexion during stance, and lower overall ankle range of motion over the gait cycle. Abbreviations: Ab, abduction; Ad, adduction; DF, dorsiflexion; Ext, extension; Flex, flexion; PF, plantarflexion.

Gait analysis was conducted at the Center for Motion Analysis in the Connecticut Children's Medical Center. The institutional review boards of the University of Connecticut and Connecticut Children's Medical Center approved the experimental protocol, and each subject provided informed consent in accordance with institutional policy.

Three-dimensional kinematics were collected using a video-based motion analysis system[a] to track 20 passive reflective markers. Markers were aligned with respect to bony landmarks and on the lower extremities, pelvis, and trunk. Lower-extremity joint angles were computed from the marker kinematics using a Euler angle notation (fig 1). Ground reaction forces were measured by 3 force platforms[b] fixed into the floor along an 11-m walkway. Three-dimensional joint moments and powers were computed at the ankle, knee, and hip using Newtonian mechanics with measured ground reactions, body segment kinematics, joint center positions, and anthropometric estimates of segment mass and moments of inertia as inputs. Joint powers were normalized to body mass to facilitate comparison across subjects. For each trial, peak joint power generation and absorption were extracted from the joint power time histories at characteristic times during gait[19] (fig 2). In addition, peak joint angles and angular excursions at the ankle, knee, and hip were assessed during the stance and swing phases of gait. A complete description of the gait data collection and reduction techniques are provided elsewhere.[7,20]

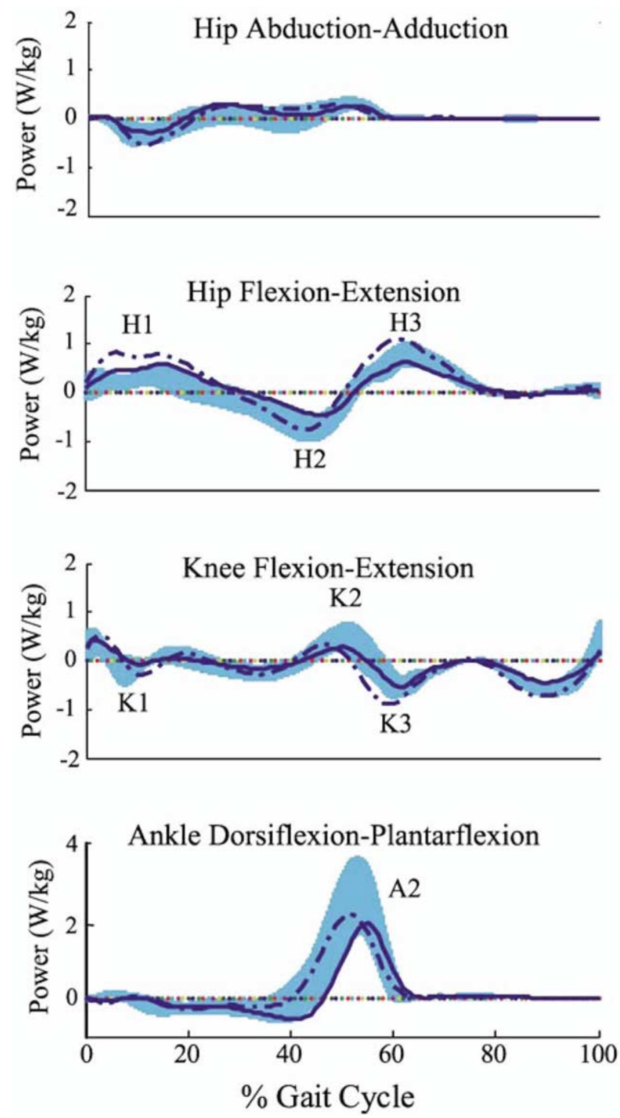

Fig 2. Joint powers throughout the gait cycle for the healthy elderly subjects walking at a comfortable gait speed (shaded curve representing mean ±1 SD) and low-performance elderly adults walking at comfortable (solid line) and fast (broken line) gait speeds. Heel strike occurs at 0% of the gait cycle. Compared with the healthy elders, the low-performance group produced less ankle power (A2) during late stance while generating greater hip extensor power (H1) during early stance.

Table 3: Spatiotemporal and Joint Kinematics Measures for the Healthy Elders at a Comfortable Speed (HC) and Low-Performance Elders at Both Comfortable (LC) and Fast (LF) Gait Speeds

Measures	HC: Healthy Comfortable Gait Speed	LC: Low-Performance Comfortable	LF: Low-Performance Fast	*P* (HC-LC)*	*P* (HC-LF)*	*P* (LC-LF)†
Single limb support (% gait cycle)	36.8±2.4	36.7±2.7	38.5±2.7	.839	.497	<.001
Step length (cm)	55.4±7.4	58.0±8.2	64.7±11.3	.042	.246	<.001
Cadence (steps/min)	115.4±7.2	105.6±7.9	127.0±15.3	<.001	.192	<.001
Walking speed (cm/s)	104.9±16.5	102.6±16.3	134.2±25.5	.881	.189	<.001
Joint kinematics (deg)						
Pelvis						
Anterior tilt	13±5	16±7	16±7	.125	.308	.159
Sagittal ROM	3±1	3±2	4±2	.206	.002	.006
Coronal ROM	6±2	7±2	8±2	.029	.178	.029
Transverse ROM	8±2	9±4	12±5	.019	.011	.003
Hip						
Abduction at toe-off	2±3	3±4	2±4	.182	.285	.490
Sagittal ROM	43±5	43±5	46±6	.731	.781	.004
Coronal ROM	10±3	11±3	12±3	.155	.466	.228
Transverse ROM	15±4	14±4	15±4	.985	.870	.006
Peak extension in stance	8±7	2±11	3±12	.018	.036	.250
Peak flexion in swing	34±6	40±10	43±10	.010	.017	<.001
Knee						
Sagittal ROM	55±4	57±5	58±6	.060	.201	.009
Ankle						
Peak dorsiflexion	12±3	9±4	7±4	.001	<.001	<.001
Peak plantarflexion	14±4	14±6	15±5	.570	.885	.637
Sagittal ROM	26±6	23±4	21±4	.064	.001	.007

NOTE. Values are mean ± SD.
Abbreviation: ROM, range of motion.
*Group effect, analysis of covariance (ANCOVA).
†Speed effect, paired *t* tests.

Experimental data were collected while both the healthy and low-performing elderly adults walked at a comfortable speed. The gait of the low-performance elders was also measured at a fast gait speed, in which the subjects were instructed to "walk as fast as you can without running or without feeling that you will trip or fall." A minimum of 3 trials were collected for each limb of each subject at the speeds tested. Kinematic and power measures from the left and right sides were averaged for each subject and used in the statistical analyses.

We used paired *t* tests to determine the effect of walking speed (comfortable, fast) on peak joint powers and kinematic variables among the low-performing elderly. We used analysis of covariance to assess group differences in peak joint powers and joint kinematics between the healthy and low-performing elderly, both walking at a comfortable speed, and between healthy elderly walking at a comfortable speed and low-performing elderly walking at a fast speed. We included normalized gait speed (normalized to subject height) as a covariate in these analyses to distinguish any effects that are attributable to gait speed variability. All statistical analyses were completed with Systat.[c] A significance level of .05 was used for all comparisons.

RESULTS

Spatiotemporal Measures

There was no significant difference in the comfortable walking speed between the healthy and low-performance elders (table 3). However, the low-performance group did walk with a slightly slower average cadence (105 steps/min) and longer (2cm) step length than the healthy group (mean, 115 steps/min). When asked to walk as fast as possible, the low-performance elders increased cadence by 20% and step length by 12% to achieve a walking speed that was 30% faster on average than the comfortable speed. The percentage of the gait cycle spent in single support did not vary between the groups but did increase significantly with walking speed in the low-performance elderly.

Kinematics

Differences in joint kinematics between the healthy and low-performance elderly were observed (see fig 1). At a comfortable gait speed, low-performance elders exhibited greater coronal and transverse pelvis rotations, reduced hip extension during late stance, greater hip flexion during swing, and less ankle dorsiflexion during stance than did the healthy elders (see table 3). When the low-performing elders increased walking speed, most of the kinematic variables changed significantly, with the notable exception that both peak hip extension and peak ankle plantarflexion remained the same as that seen at a comfortable gait speed. In addition, the low-performing elders persisted at the fast gait speed to exhibit reduced peak hip extension, less hip flexion in swing, less dorsiflexion, and greater transverse pelvic rotation than the healthy elders.

Joint Powers

Significant differences in peak joint powers at the hip and ankle were evident between the groups (table 4). Compared with the healthy elders at a comfortable gait speed, the low-performance group generated significantly less ankle plantarflexor power (A2) during late stance but greater hip extensor power (H1) during early support at a comfortable walking speed (see fig 2). To walk faster, peak joint power generation and absorption increased significantly at the ankle, knee, and

Table 4: Peak Joint Powers, Normalized to Body Mass (W/kg), of the Healthy Elderly and Low-Performance Elderly

	HC: Healthy Comfortable Gait Speed	LC: Low-Performance Comfortable	LF: Low-Performance Fast	*P* (HC-LC)*	*P* (HC-LF)*	*P* (LC-LF)†
Hip						
H1	0.48±0.25	0.80±0.39	1.17±0.54	<.001	<.001	<.001
H2	−0.76±0.25	−0.59±0.37	−0.93±0.57	.070	.296	<.001
H3	0.91±0.21	0.83±0.39	1.39±0.58	.484	.153	<.001
Knee						
K1	−0.24±0.31	−0.12±0.12	−0.37±0.29	.093	.593	<.001
K2	0.15±0.16	0.15±0.18	0.24±0.15	.895	.376	.015
K3	−0.70±0.18	−0.86±0.55	−1.40±0.85	.108	.052	<.001
Ankle						
A1	−0.64±0.20	−0.71±0.13	−0.60±0.20	.085	.993	.006
A2	3.00±0.88	2.13±0.58	2.59±0.70	<.001	.002	.007

NOTE. Values are mean ± SD.
*Group effect, ANCOVA.
†Speed effect, paired *t* tests.

hip. Ankle power output during late stance increased an average of 23% with speed, whereas hip peak flexor power generation (H1), absorption (H2), and extensor power generation (H3) increased an average of 54%, 57%, and 67%, respectively, at the fast walking speed. Despite walking much faster than the healthy elderly adults, ankle power generation during fast gait remained significantly below the ankle power output of the healthy elders at a comfortable gait.

DISCUSSION

We compared peak joint power and kinematic variables between comfortable and fast walking speeds among a group of elderly adults with impairments in physical performance. Contrary to our hypothesis, we found that both hip and ankle power outputs increased significantly with speed, suggesting that ankle muscle power capacity was not strictly a limiting neuromuscular factor in normal walking. However, ankle power output among the low-performing elders remained diminished compared with the healthy adults, ever when walking at a faster gait speed.

A number of studies have shown that ankle plantarflexor power and work done during late stance is reduced in healthy elderly compared with healthy young adults.[4,8,9] For example, DeVita and Hortobagyi[8] found that healthy elderly generated significantly less work at the ankle and knee, but greater hip extensor work during early stance, when walking at the same speed as a group of healthy young adults. These changes were interpreted as a distal to proximal shift in the locus of neuromuscular function with aging.[8] Although the exact methods and details differ, others have also reported that healthy elders seem to use adaptations at the hip to compensate for reduced plantarflexor power output.[7,12]

McGibbon and Krebs[11-13] were the first to show that frail elderly with functional limitations show even further declines in ankle power output during walking. Similar observations have been made of elders with a history of falls[14,21] and are now also shown in our analysis of elders with low physical performance. An important observation in this study was that even when the low-performance elders increased walking speed to a magnitude that was 30% greater than the healthy elderly, ankle power output remained significantly diminished. The only other significant difference in joint powers that was evident in the low-performing elderly, relative to the healthy group, was an increased hip extensor power during early stance. McGibbon and Krebs[12] have also reported impairment-related changes in hip kinetics, although they suggest the primary change is toward greater eccentric hip work during midstance. Whether the difference between studies is attributable to differences in the methodology used or characteristics of the population is not clear.

During late stance, the ankle muscles are generally believed to propel the stance limb into swing, and may also produce substantial forward and vertical acceleration of the upper body.[22] Given the relatively close timing between the ankle plantarflexor power output during late stance and the contralateral hip extensor power generation during early support (see fig 2), it is feasible that the proximal muscle actions about the hip may compensate for reduced mechanical actions at the ankle. McGibbon[23] has recently speculated on various mechanical means by which hip muscle actions may compensate for reduced ankle power. Future studies that can quantitatively identify such compensatory mechanisms are warranted.

Ankle muscle weakness has been suggested as a possible cause of reduced ankle power output in elderly gait.[4,9] Indeed, maximum ankle power capacities of healthy elderly are 20% to 40% below that of young adults,[6] a difference that is likely even more marked among impaired elders. However, in this study the impaired elderly tested did indeed increase ankle power output (24%) to walk faster, which strongly suggests that as a group, ankle power output was not a strictly limiting factor. Of potential importance are the kinematic changes between the healthy and low-performance elders. Relative to the healthy elderly, the low-performance group showed larger transverse pelvic rotations, reduced peak ankle dorsiflexion, and a shift to greater hip flexion and less hip extension. These differences, which may arise from tightness in the hip flexors and ankle plantarflexors, are similar to the differences seen between healthy young and healthy old adults.[7] For example, the healthy elderly exhibited a 3° shift in hip range of motion (ROM) toward greater hip flexion compared with young adults.[7] In the present study, the low-performance group had an additional 6° shift toward hip flexion, for a total of 9° hip ROM shift compared with young adults.[7] It is notable that hip extension did not increase with walking speed among the low-performing elders, suggesting that it indeed may be a limiting factor. Kerrigan et al[14] have also found that a large reduction in hip extension was the primary kinematic factor that distinguished the gait of elderly fallers from healthy young and elderly adults. The larger transverse pelvic rotations used by the low-performing elders may be a mechanism to increase step length, and conversely gait speed, in the presence of reduced hip flexibility.

The shift with impairment toward a more flexed hip may have substantial effects on the mechanical function of muscles, which in turn may necessitate compensatory changes in coordination. Experimental evidence in support of this effect can be found in the recent results of an intervention study by Kerrigan et al.[15] They found that 10 weeks of performing a simple hip flexor stretching exercise increased hip extension during gait and, more surprisingly, also tended to increase ankle power output at a preferred gait speed. These results show the potentially important effect that slight changes in posture may have on muscle function in gait.[24]

The primary discriminating factor between the 2 elderly groups in this study was that the low-performance elderly group demonstrated performance decrements in an SPPB, which has been shown to identify persons at higher risk of developing mobility-related disability, and to be admitted to a nursing home.[17] However, given the diverse physical impairments that these subjects showed on clinical examination (see table 2), there may well be variable reasons for the changes in gait observed in this group. Our limited subject numbers do not allow us to further subdivide the group based on chronic conditions. McGibbon et al[13] found differences in gait mechanics between functionally limited elders who had primarily orthopedic impairments, compared with functionally limited elders with nonorthopedic impairments. In particular, people with orthopedic impairments, primarily arthritis, tended to utilize greater mechanical energy expenditure from the hip and low-back and less energy expenditure from the ankle.[13] Despite the wide variety of chronic conditions that the low-performance group members had (see table 2), we observed similar changes whereby low-performing elders relied on hip muscle actions to compensate for reductions in ankle muscle power. Thus, this study provides further evidence of potential common kinematic and kinetic changes as mobility and performance declines in later life.

Although this study and others[11-14,23] have shown significant differences in joint mechanics between healthy elders and impaired elders, it remains challenging to translate this information into clinically effective interventions for maintaining normal gait mechanics among impaired elderly. This challenge stems both from the difficulties in understanding the interdependence of kinematic and kinetic measures, for example, effect of hip flexibility on ankle power output,[15] and from the intrasubject errors associated with individual gait measures,[25] which can be on the same order of magnitude of some of the intergroup differences found in this study. Therefore, the clinician still is often not able to reliably measure how specifically a person's gait differs from normal, or predict how specific changes in joint power or ROM will affect the gait of an individual. What can clinicians and exercise leaders do while waiting for more definitive studies and measures? From a public health perspective, it appears prudent for older adult exercise programs to include activities that safely address the identified components of gait that seem most likely to be limiting factors in older adults—hip extension and ankle ROM, and ankle plantarflexor strength/power.

CONCLUSIONS

This study shows that the large and significant differences in ankle and hip kinematics and kinetics between a low-performing group and a healthy group of older subjects cannot be attributed strictly to strength deficits or differences in walking speed. Future work designed to investigate the interdependence of joint ROM and muscle power limitations seem critical to inform interventions to maintain gait into advanced age.

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Suppliers

a. Vicon Motion Measurement Systems Inc, 9 Spectrum Pointe Dr, Lake Forest, CA 92630.
b. Advanced Medical Technology Inc, 176 Waltham St, Watertown, MA 02472.
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