JOURNAL OF WOMEN'S HEALTH & GENDER-BASED MEDICINE
Volume 11, Number 5, 2002

Gender Differences in Pelvic Motions and Center of Mass Displacement during Walking: Stereotypes Quantified

LYNNELLE K. SMITH,[1] JENNIFER L. LELAS, M.S.,[1] and D. CASEY KERRIGAN, M.D., M.S.[2]

ABSTRACT

Objectives: **A general perception that women and men walk differently has yet to be supported by quantitative walking (gait) studies, which have found more similarities than differences. Never previously examined, however, are pelvic and center of mass (COM) motions. We hypothesize the presence of gender differences in both pelvic obliquity (motion of the pelvis in the coronal plane) and vertical COM displacement. Quantifiable differences may have clinical as well as biomechanical importance.**

Methods: **We tested 120 subjects separated into four groups by age and gender. Pelvic motions and COM displacements were recorded using a 3-D motion analysis system and averaged over three walking trials at comfortable walking speed. Data were plotted, and temporal values, pelvic angle ranges, and COM displacements normalized for leg length were quantitatively compared among groups.**

Results: **Comparing all women to all men, women exhibited significantly more pelvic obliquity range (mean ISD): 9.4 ± 3.5 degrees for women and 7.4 ± 3.4 degrees for men ($p = 0.0024$), and less vertical COM displacement: 3.7 ± 0.8% of leg length for women and 3.3 ± 0.9% for men ($p = 0.0056$).**

Conclusions: **Stereotypically based gender differences were documented with greater pelvic obliquity and less vertical COM displacement in women compared with men. It is unclear if these differences are the intrinsic result of gender vs. social or cultural effects. It is possible that women use greater pelvic motion in the coronal plane to reduce their vertical COM displacement and, thus, conserve energy during walking. An increase in pelvic obliquity motion may be advantageous from an energy standpoint, but it is also associated with increased lumbosacral motion, which may be maladaptive with respect to the etiology and progression of low back pain.**

INTRODUCTION

THERE IS A COMMON PERCEPTION that an inherent difference exists between the walking styles of women and men. For instance, observers can consistently identify the gender of a person walking in the sagittal plane, based solely on the dynamic light displays of the subject's joints.[1] Despite this perception, previous quantitative studies of gait have failed to find substantial differences.[1–7] These studies have shown not only that kinematic and kinetic joint patterns are very sim-

[1]Center for Rehabilitation Science, Spaulding Rehabilitation Hospital, Boston, Massachusetts.
[2]Department of Physical Medicine and Rehabilitation, Harvard Medical School, Boston, Massachusetts.
This study was supported by the Ellison Foundation and the Public Health Service (grant K24 HD01351).

ilar between genders but also that women tend to walk at the same velocity as men.[2,4,6,7] Women are observed to walk at significantly higher cadences and with shorter step lengths than men,[4,6,7] and when normalized for stature, women have the same length steps.[2]

Although previous studies have reported many similarities between genders, we are unaware of any study that has quantified and statistically compared pelvic and center of mass (COM) motions. We believe that differences in pelvic and COM motions exist and may be responsible for the stereotypical styles of walking in women and men. Specifically, we hypothesize that women compared with men have increased pelvic obliquity (up and down hip movement in the coronal plane). Pelvic obliquity has been identified as a mechanism to reduce the energy requirement of walking by dropping the vertical summit of the COM's path during walking, such that the vertical displacement of the COM is reduced.[8–11] Thus, we hypothesize that women also have less vertical COM displacement (normalized for leg length) than men.

MATERIALS AND METHODS

Pelvic motion and vertical and mediolateral COM displacement (using the sacrum, a proven estimate measure of COM displacement)[12] were recorded in 120 healthy volunteers at their chosen comfortable walking pace. These people were equally divided into two age groups, young adults and elderly, each with 30 men and 30 women. Our Institutional Review Board approved this study protocol, and a written informed consent was obtained from each subject. All the women and men comprising both groups were without history of cardiovascular, pulmonary, neurological, or orthopedic disease. The young women ranged in age from 22 to 40 years (mean 29.0 ± 5.9), mean weight 57.4 ± 12.2 kg, and mean height 1.6 ± 0.07 m, and the young men ranged in age from 22 to 40 years (mean 30.3 ± 6.3), mean weight 79.3 ± 10.7 kg, and mean height 1.8 ± 0.05 m. The elderly women ranged in age from 66 to 83 years (mean 72.2 ± 4.7), mean weight 62.1 ± 10.5 kg, and mean height 1.6 ± 0.06 m, and the elderly men ranged in age from 65 to 83 years (mean 71.6 ± 4.9), mean weight 77.6 ± 12.4 kg, and mean height 1.7 ± 0.07 m. There were no significant differences in age between the two young adult groups or between the two elderly adult groups.

Subjects were asked to first stand and then walk barefoot at their comfortable walking speed across a 10-m long gait laboratory walkway. Pelvic obliquity (motion in the coronal plane), pelvic rotation (motion in the transverse plane), pelvic tilt (motion in the sagittal plane), and COM (vertical and mediolateral) motions were recorded over three trials. The methods to record these motions are based on standard techniques and have been described previously.[9,10,13–16] With respect to the pelvis, markers were placed over the sacrum and bilaterally on the anterior superior iliac spines. Additional markers were attached to wands and placed bilaterally over the midfemur and midshank. A six-camera video-based motion analysis system (VICON 512 system, Oxford Metrics Ltd., Oxford, U.K.) was used to measure the three-dimensional (3-D) position of the markers at 120 frames per second. The standing leg length was obtained by measuring the distance from the sacral marker to the floor as the subject stood upright. The raw vertical and mediolateral COM displacement and average peak pelvic motions were averaged over the same three trials at normal walking speed.

To control for differences in stature, we normalized both vertical and mediolateral COM displacement by leg length, specifically, the height of the sacrum from the ground when standing comfortably. We reported both vertical and mediolateral COM displacement as a percentage of leg length.

Comparisons were made between genders and age groups using unpaired t tests, with statistical significance defined at $p < 0.05$, although trends toward significance with $p < 0.10$ also were noted. Women and men were compared collectively and then within the two age groups.

RESULTS

The results for the temporal parameters are listed in Table 1. When comparing the temporal parameters of all 60 women to all 60 men regardless of age, there were no gender differences in walking velocity, although women had significantly higher cadences ($p < 0.0001$) and shorter stride lengths than men ($p < 0.0001$). Similar results were observed both in the comparison between young women and men ($p \leq 0.0012$ for ca-

TABLE 1. TEMPORAL DATA

Parameter	All 60 men	All 60 women	Young men	Young women	Elderly men	Elderly women
Velocity (mm/sec)	1248.4 ± 203.05	1224.9 ± 146.5	1309.5 ± 196.3	1270.2 ± 132.1	1187.4 ± 194.0	1179.6 ± 148.3
	$p = 0.4676$		$p = 0.3670$		$p = 0.8612$	
Cadence (1/sec)	0.93 ± 0.07	1.00 ± 0.08	0.93 ± 0.08	0.99 ± 0.07	0.94 ± 0.06	1.01 ± 0.08
	$p < 0.0001$		$p = 0.0012$		$p = 0.0001$	
Stride length (SL) (mm)	1334.5 ± 159.4	1219.0 ± 116.7	1407.1 ± 132.3	1282.0 ± 92.2	1261.8 ± 152.5	1155.9 ± 104.8
	$p < 0.0001$		$p < 0.0001$		$p = 0.0027$	

dence and stride length) and in the comparison between elderly women and men ($p \leq 0.0027$ for cadence and stride length). Velocity ($p \leq 0.0185$) and stride length ($p \leq 0.0002$) were significantly less in the elderly group than in the young adult group for respective genders.

The pelvic motion and COM displacement comparisons are shown in Tables 2 and 3, respectively. For all 120 subjects tested (60 women and 60 men), women had a significantly greater range of pelvic obliquity (9.4 ± 3.5 degrees for women, 7.4 ± 3.4 degrees for men, $p = 0.0024$) and significantly lower normalized vertical COM displacement (3.7 ± 0.8% leg length for women, 3.3±0.7% leg length for men, $p = 0.0056$).

The comparisons between the young women and men yielded similar results to those found between the genders as a whole, but the differences were not quite statistically significant. Young women had a tendency toward both increased pelvic obliquity range (11.1 ± 3.2 degrees vs. 9.6 ± 3.3 degrees for men, $p = 0.0794$) and less normalized vertical COM displacement (3.8 ± 0.9% vs. 3.4 ± 0.8% leg length, $p = 0.0995$).

Comparisons between the elderly women and elderly men demonstrated significantly higher pelvic obliquity range in women compared with men (7.7 ± 3.1 degrees for women, 5.3 ± 1.9 degrees for men, $p = 0.0005$). Elderly women compared to elderly men also showed a trend toward higher pelvic tilt range (2.4 ± 1.1 degrees for women, 1.8 ± 1.0 degrees for men, $p = 0.0530$) as well as a trend toward greater pelvic rotation range (10.9 ± 4.4 degrees for women, 8.9 ± 4.0 degrees for men, $p = 0.0671$). Elderly women also had significantly less normalized vertical COM displacement (3.2 ± 0.6% leg length for women, 3.6 ± 0.7% leg length for men, $p = 0.0163$).

DISCUSSION

As hypothesized, we found that women generally have greater pelvic obliquity during walking than men. Although the gender difference in pelvic obliquity was not quite statistically significant in the young adult group, it was statistically significant for the population as a whole and for

TABLE 2. PELVIC MOTION DATA

Parameter	All 60 men	All 60 women	Young men	Young women	Elderly men	Elderly women
Pelvic obliquity range (degrees)	7.4 ± 3.4	9.4 ± 3.5	9.6 ± 3.3	11.1 ± 3.2	5.3 ± 1.9	7.7 ± 3.1
	$p = 0.0024$		$p = 0.0794$		$p = 0.0005$	
Pelvic tilt range (degrees)	2.1 ± 1.0	2.3 ± 1.0	2.3 ± 1.0	2.3 ± 0.7	1.8 ± 1.0	2.4 ± 1.2
	$p = 0.1818$		$p = 0.8060$		$p = 0.0530$	
Pelvic rotation range (degrees)	10.4 ± 4.1	11.4 ± 4.2	11.8 ± 3.6	11.9 ± 3.9	8.91 ± 4.0	10.9 ± 4.4
	$p = 0.1673$		$p = 0.9592$		$p = 0.0671$	

TABLE 3. COM DISPLACEMENT DATA

Parameter	*All 60 men*	*All 60 women*	*Young men*	*Young women*	*Elderly men*	*Elderly women*
Vertical COM displacement (mm)	36.7 ± 8.2	30.0 ± 6.3	38.5 ± 9.3	31.1 ± 6.6	34.9 ± 6.7	28.8 ± 5.9
	$p < 0.0001$		$p = 0.0008$		$p = 0.0004$	
Normalized vertical COM displacement (%)[a]	3.7 ± 0.8	3.3 ± 0.7	3.8 ± 0.9	3.4 ± 0.8	3.6 ± 0.7	3.2 ± 0.6
	$p = 0.0056$		$p = 0.0995$		$p = 0.0163$	
Mediolateral COM displacement (mm)	51.1 ± 12.8	48.2 ± 13.5	51.5 ± 14.9	45.5 ± 10.1	50.7 ± 10.6	50.9 ± 15.8
	$p = 0.2306$		$p = 0.0751$		$p = 0.9604$	
Normalized mediolateral COM displacement (%)[a]	5.0 ± 1.0	5.0 ± 1.0	5.0 ± 1.0	5.0 ± 1.0	5.0 ± 1.0	6.0 ± 2.0
	$p = 0.5901$		$p = 0.8635$		$p = 0.3610$	

[a]Percent of leg length.

the elderly group. This is the first study of which we are aware that demonstrates a quantifiable difference in gait kinematics and supports the perceived notion that women and men walk differently. Why women have greater pelvic obliquity and why it appears to be more prominent in elderly women are unclear. Differences in pelvic anatomy or societal or cultural factors might explain these differences. There also may be an underlying energetic basis for greater pelvic obliquity. Previous studies have supported that pelvic obliquity is a mechanism to reduce vertical COM displacement, thus conserving energy required to walk.[8–11] Indeed, we found that women compared with men generally have reduced vertical COM displacement, even when normalized for leg length (statistically significant in comparing all women and in comparing elderly women to elderly men). A reduction in vertical COM displacement implies a more biomechanically efficient gait, at least in terms of the work required to lift the COM per one unit of walking distance[8–11,17] (Kerrigan, 1996, 17457) Thus, greater pelvic obliquity in women compared with men may represent a mechanism to reduce vertical COM displacement and conserve energy during walking.

Interestingly, although the gender differences in pelvic obliquity and normalized COM displacement were statistically significant between all women and all men and between the elderly women and elderly men, they were not statistically significant between the young adult groups. Perhaps there are inherent gender differences that increase with age, or perhaps there are learned generational differences in walking that significantly affect both pelvic motion and COM displacement. Clearly, there is considerable overlap in the amount of both pelvic and COM motions between women and men, and there are likely other influences besides gender that affect these variables. It may be that women as they age use a greater amount of pelvic obliquity than men to reduce COM displacement and conserve energy. Alternatively, elderly women and elderly men may be more sensitive to cultural cues, for example, "Walk like a lady," or "Don't act like a sissy."

Although greater pelvic obliquity in women may be beneficial with respect to biomechanical energy considerations, greater pelvic obliquity may be maladaptive with respect to the lumbosacral spine. It has been pointed out that pelvic obliquity motions are linearly related to lower lumbar spinal movement,[18,19] implying that women during walking have greater intervertebral lumbosacral motions than men. Lumbosacral motion is implicated as an important etiological factor in the development and progression of disc disease.[20] In fact, reducing lumbosacral motion and associated increased lumbar intradiscal pressures[21] is the goal of several treatments, including postural training and orthoses, to reduce acute and chronic low back pain or disc degeneration.[22] Thus, the increased pelvic obliquity observed in women may have functional implications with respect to both the etiology and progression of acute and chronic low back pain.

It may be that different walking styles can be adopted to change pelvic obliquity without substantially affecting COM displacement, and it would be worthwhile to study this possibility. It also would be worthwhile to study the effects of different types of women's shoes on pelvic obliquity and COM displacement. Kerrigan et al.[23,24] found that different high-heeled shoes increase torques about the knee that may predispose to knee osteoarthritis, but a critical evaluation of pelvic and COM motion occurring with different types of shoes has yet to be performed. The present study is the first to quantify a substantial gender biomechanical difference in walking. Clearly, further studies of these parameters that may have important clinical and biomechanical relevance are warranted.

CONCLUSIONS

Despite similarities between genders found in previous quantitative gait studies, we have identified and quantified gender differences in pelvic and COM motions during walking that support the perception that women and men walk differently. As hypothesized, women have greater pelvic obliquity range but less normalized vertical COM displacement than men. Differences were more pronounced as a function of increasing age. It is unclear if these differences are the intrinsic result of gender vs. social or cultural effects. It is possible that women use greater pelvic motion in the coronal plane to reduce their vertical COM displacement and thus conserve energy during walking. An increase in pelvic obliquity motion may be advantageous from an energy standpoint but is also associated with increased lumbosacral motion that may be maladaptive with respect to the etiology and progression of low back pain.

ACKNOWLEDGEMENTS

We thank Pat O. Riley, Ph.D., for serving as a scientific advisor, Ugo Della Croce, Ph.D., for his technical assistance, and Meaghan J. Sullivan, B.A., for collecting data and revision assistance. We also acknowledge Advanced Mechanical Technology Inc. (AMTI), Newton, Massachusetts.

REFERENCES

1. Cutting JE, Proffitt DR, Kozlowski LT. A biomechanical invariant for gait perception. J Exp Psychol Hum Percept Perform 1978;4:357.
2. Kerrigan DC, Todd MK, Della Croce U. Gender differences in joint biomechanics during walking: Normative study in young adults. Am J Phys Med Rehabil 1998;77:2.
3. Bhambhani Y, Singh M. Metabolic and cinematographic analysis of walking and running in men and women. Med Sci Sports Exerc 1985;17:131.
4. Richard R, Weber J, Mejjad O, et al. Spatiotemporal gait parameters measured using the Bessou gait analyzer in 79 healthy subjects. Influence of age, stature, and gender. Study Group on Disabilities due to Musculoskeletal Disorders (Groupe de Recherche sur le Handicap de l'Appareil Locomoteur, GRHAL). Rev Rhum [English edition] 1995;62:105.
5. Bhambhani Y, Maikala R. Gender differences during treadmill walking with graded loads: Biomechanical and physiological comparisons. Eur J Appl Physiol 2000;81:75.
6. Sato H, K. I. Gait patterns of Japanese pedestrians. J Hum Ergol 1990;19:13.
7. Finley FR, Cody KA. Locomotive characteristics of urban pedestrians. Arch Phys Med Rehabil 1970;51:423.
8. Saunders JBD, Inman VT, Eberhart HD. The major determinants in normal and pathological gait. Am J Bone Joint Surg 1953;35:543.
9. Kerrigan DC, Croce UD, Marciello M, Riley PO. A refined view of the determinants of gait: Significance of heel rise. Arch Phys Med Rehabil 2000;81:1077.
10. Kerrigan DC, Riley PO, Lelas JL, Della Croce U. Quantification of pelvic rotation as a determinant of gait. Arch Phys Med Rehabil 2001;82:217.
11. Della Croce U, Riley PO, Lelas JL, Kerrigan DC. A refined view of the determinants of gait. Gait Posture 2001;14:79.
12. Saini M, Kerrigan DC, Thirunarayan MA, Duff-Raffaele M. The vertical displacement of the center of mass during walking: A comparison of four measurement methods. J Biomech Eng 1998;120:133.
13. Kadaba MP, Ramakrishnan HK, Wootten ME, Gainey J, Gorton G, Cochran GV. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. J Orthop Res 1989;7:849.
14. Winter DA. Biomechanics and motor control of human movement, Series 2. New York: John Wiley & Sons, 1990:
15. Kadaba MP, Ramakrishnan HK, Wootten ME. Measurement of lower extremity kinematics during level walking. J Orthop Res 1990;8:383.
16. Kerrigan DC, Edelstein JE. Gait. In: Gonzalez EG, My-

ers SJ, Edelstein JE, Lieberman JS, eds. Boston: Butterworth-Heinemann, 2001:397.

17. Kerrigan DC, Viramontes BE, Corcoran PJ, LaRaia PJ. Measured versus predicted vertical displacement of the sacrum during gait as a tool to measure biomechanical gait performance. Am J Phys Med Rehabil 1995;74:3.
18. Whittle MW, Levine D. Three-dimensional relationships between the movements of the pelvis and lumbar spine during normal gait. Hum Mov Sci 1999; 18:681.
19. Selles RW, Wagenaar RC, Smit TH, Wuisman PI. Disorders in trunk rotation during walking in patients with low back pain: A dynamical systems approach. Clin Biomech 2001;16:175.
20. Bernhardt M, White AA, Panjabi MM. Biomechanical considerations of spinal stability. In: Herkowitz HN, Garfin SR, Balderston RA, Eismont FJ, Bell GR, Wiesel SW, eds. Biomechanical considerations of spinal stability. Philadelphia: WB Saunders Company, 1999.
21. Nachemson A. Lumbar intradiscal pressure. In: Jayson MI, ed. Lumbar intradiscal pressure. New York: Churchill Livingstone, Inc, 1987.
22. Botte MJ, Garfin SR, Bergmann K, Byrne TP, Vaccaro AR. Spinal orthoses for traumatic and degenerative disease. In: Herkowitz HN, Garfin SR, Balderston RA, Eismont FJ, Bell GR, Wiesel SW, eds. Spinal orthoses for traumatic and degenerative disease. Philadelphia: W.B. Saunders Company, 1999.
23. Kerrigan DC, Todd MK, Riley PO. Knee osteoarthritis and high-heeled shoes. Lancet 1998;351:1399.
24. Kerrigan DC, Lelas JL, Karvosky ME. Women's shoes and knee osteoarthritis. Lancet 2001;357:1097.

Address reprint requests to:
Dr. Casey Kerrigan, M.D., M.S.
Professor and Chair
University of Virginia Department of Physical Medicine and Rehabilitation
545 Ray C. Hunt Drive, Suite 240
Charlottesville, VA 22908-1004