GENDER DIFFERENCES IN JOINT BIOMECHANICS DURING WALKING

Normative Study in Young Adults[1]

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The effect of gender on specific joint biomechanics during gait has been largely unexplored. Given the perceived, subjective, and temporal differences in walking between genders, we hypothesized that quantitative analysis would reveal specific gender differences in joint biomechanics as well. Sagittal kinematic (joint motion) and kinetic (joint torque and power) data from the lower limbs during walking were collected and analyzed in 99 young adult subjects (49 females), aged 20 to 40 years, using an optoelectronic motion analysis and force platform system. Kinetic data were normalized for both height and weight. Female and male data were compared graphically and statistically to assess differences in all major peak joint kinematic and kinetic values. Females had significantly greater hip flexion and less knee extension before initial contact, greater knee flexion moment in pre-swing, and greater peak mechanical joint power absorption at the knee in pre-swing ($P < 0.0019$ for each parameter). Other differences were noted ($P < 0.05$) that were not statistically significant when accounting for multiple comparisons. These gender differences may provide new insights into walking dynamics and may be important for both clinical and research studies in motivating the development of separate biomechanical reference databases for males and females.

Key Words: Gait, Biomechanics, Kinetics, Kinematics, Human, Adult, Male, Female, Gender Factors

Most will agree that males and females walk differently. Moreover, an individual can properly identify the correct gender based solely on impoverished light displays of a subject's joints during walking in the sagittal plane.[1] However, despite acknowledged overall movement differences between genders, specific differences in biomechanics about the hip, knee, and ankle are not clear and, to date, have received very little study. Meanwhile, biomechanical gait analysis is increasingly applied in rehabilitation settings to assist in therapeutic decision-making.[2-4] The study of joint biomechanics, including the study of both joint motion (kinematics) and joint torques and powers (kinetics) during gait is crucial to enhancing our understanding of gait dynamics in general.[5-8]

The literature is replete with information regarding temporal gait parameter differences between males and females. On average, females walk at higher cadences compared with males.[9-13] Females also have slightly shorter stride lengths,[9, 10, 12-16] although when normalized for height, females tend to have the same or slightly greater stride lengths.[13-15] Despite these cadence and stride length differences, females and males tend to have the same comfortable speed of walking, at least in controlled laboratory environments.[9, 13, 17]

Given these temporal gait parameter differences, as well as perceptions of gender differences in gait patterns, we expected to also find specific joint kinematic and kinetic differences between genders. Most kinematic studies on adult subjects have included predominantly male or female subjects or have inadequate sample sizes in the young adult age range, which precludes valid gender comparisons.[14, 15, 18-21] Admittedly, the main purpose of these previous studies has not been to assess gender differences but rather to demonstrate the feasibility of a particular kinematic measurement device[18-20, 22-24] or to evaluate age-related kinematic changes.[14, 15, 21, 25] Although little attention has been given to kinematic

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differences, even less attention has been given to potential kinetic differences or similarities between genders. Some studies evaluated ground reaction force measurements between genders but have not provided specific conclusions.[21, 24, 26] Moreover, we are unaware of any comprehensive study of joint kinetics during gait in young adult subjects.

The aim of this study was to systematically assess joint biomechanical gender differences during gait in healthy, young adult subjects. Both kinematic and kinetic analyses were performed. The population studied consisted of 49 females and 50 males between the ages of 18 and 39 years, with an even distribution of ages between males and females. This age group was selected to represent a mature adult gait pattern while reducing as much as possible additional questions of age-related gait changes.

METHODS

One hundred able-bodied young adult subjects aged 20 to 39 years (50 males) were recruited for this study. The data from 49 females and 50 males were analyzed. Data from one female subject were lost because of an inadvertent processing error. The population studied included fairly equivalent gender proportions of hospital employees and spouses, nearby financial district and federal building employees, and individuals not employed outside the home. Subjects with any known musculoskeletal, neurologic, cardiovascular, pulmonary, or gait disorder were excluded. The methods were approved by our Institutional Review Board, and an informed consent was obtained from each volunteer.

Subjects were asked to first stand and then walk barefoot at their comfortable walking speed across the 30-foot gait laboratory walkway. They were not asked to restrict their movement, including arm swing, in any way. Kinematic and kinetic data from bilateral sides for three walking trials were collected and analyzed. The methods used for this analysis have been described previously.[27, 28] Briefly, an optoelectronic motion analysis system (Bioengineering Technology Systems (BTS) ELITE System, Milan, Italy) was used to measure the three-dimensional coordinates of 1.5-cm hemispherical, infrared reflective markers at 100 Hz,[29, 30] attached to the subjects' skin over the following bony landmarks: the lower prominence of the sacrum, bilateral posterior superior iliac spines, lateral femoral condyles, lateral malleoli, and fifth metatarsals. Additional markers rigidly attached to wands were placed over the lateral femoral condyles, the anterior tibial shafts, and the forefeet. Four video cameras were used with two cameras placed posterolaterally on each side of the subject. The kinematic joint angle data during walking for each subject were calculated in reference to that subject's measured joint angle values during quiet standing, which defined zero degree angles at the hip, knee, and ankle. No statistically significant gender differences in absolute standing values were noted about the hip, knee, or ankle ($P > 0.05$ in each case).

Ground reaction forces were measured synchronously with the kinematic data at a sampling rate of 100 Hz using two staggered force platforms, 51 cm length by 46 cm width, (Advanced Mechanical Technology Inc. (AMTI), Newton, MA) embedded in the walkway. The locations of the force platforms in the global reference plane were predetermined by acquiring coordinates of markers placed on their corners. A commercialized protocol, SAFLo (Servizio di Analisi della Funzionalita' Locomotoria) from BTS, developed by Pedotti and Frigo,[31] was used to calculate the sagittal plane kinematics and kinetics. The following anthropometric measurements were collected according to the SAFLo protocol to calculate the kinematics and kinetics: body weight, height, pelvic width and height, thigh, foot, and lower leg length, and intracondylar and intramalleolar width. Kinetics were calculated according to standard techniques, using force platform data and inverse dynamic techniques described by Winter[5] per the SAFLo protocol. Moments and powers were normalized for body weight and height and reported as external, in Newton meters per kilogram meters (N-m/kg-m) and Watts per kilogram meters (W/kg-m), respectively. Gait velocity and stride length were obtained using the force platform and kinematic information to define initial foot contact times and distance parameters.

Kinematic and kinetic data were graphed over 2% intervals of the gait cycle. Graphs of each trial for each subject as well as the averaged data from all subjects were visually inspected. Qualitative differences in the graphs between genders were assessed. A total of 27 peak values were evaluated (Tables 1 and 2 and Fig. 1). The terminology used to define the timing of each peak is consistent with that reported by Perry.[32] A nested, mixed-effects analysis of variance model (JMP software, SAS Institute, Cary, NC) was used to assess any statistically significant interactions between gender and trial or between gender and side. Because the model demonstrated no significant interactions between gender and trial or between gender and side for any of the 27 variables, we simply averaged all six trials (3 on each side) for each subject. The averaged values from each subject were compared statistically between genders using an unpaired Student's t test. A Bonferroni adjustment was made for the multiple[27] comparisons performed. Statistical significance was, thus, defined at $P < 0.0019$ (0.05/27), although results with P values greater than 0.0019 and less than 0.05 were also noted and discussed. Demographic variables were compared using an unpaired t test, and temporal variables were compared using both the unpaired t test and nested, mixed-effects analysis of variance model. Statistical significance for each of the demographic and temporal parameters were defined at $P < 0.05$.

TABLE 1

Female v *male peak kinematic values*

(In Degrees)	Females			Males			P Values
	Mean	Intersubject (SD)	Total (SD)	Mean	Intersubject (SD)	Total (SD)	
Hip flexion	26.2	(4.2)	(5.0)	23.0	(4.1)	(4.7)	<0.001*
Hip extension	−19.7	(4.8)	(5.5)	−20.6	(4.9)	(5.5)	0.362
Knee extension before initial contact	7.1	(3.9)	(4.8)	3.7	(4.1)	(5.1)	<0.001*
Knee flexion loading response	19.1	(4.8)	(5.4)	17.4	(5.9)	(6.3)	0.113
Knee extension terminal stance	2.1	(4.0)	(4.7)	1.2	(3.0)	(3.6)	0.199
Knee flexion	61.5	(5.7)	(6.2)	59.4	(4.2)	(5.0)	0.036†
Ankle plantar flexion loading response	−7.8	(3.1)	(3.9)	−7.8	(3.2)	(3.5)	0.893
Ankle dorsiflexion mid stance	7.8	(3.1)	(3.7)	7.4	(2.6)	(3.1)	0.537
Ankle plantar flexion	−22.2	(6.0)	(7.5)	−19.3	(5.5)	(6.3)	0.014†
Ankle dorsiflexion swing	1.3	(3.3)	(4.0)	0.9	(3.0)	(3.4)	0.517

* Statistically significant difference at $P < 0.05/27 = 0.0019$.

† Near significant difference at $0.05/27 < P < 0.05$.

TABLE 2

Female v *male peak biomechanical gait values*

	Females			Males			P Values
	Mean	Intersubject (SD)	Total (SD)	Mean	Intersubject (SD)	Total (SD)	
Hip flexion moment stance (N · m/Kg · m)	0.44	(0.10)	(0.12)	0.40	(0.09)	(0.11)	0.073
Hip extension moment (N · m/Kg · m)	0.57	(0.15)	(0.17)	0.56	(0.14)	(0.15)	0.700
Hip flexion moment swing (N · m/Kg · m)	0.11	(0.05)	(0.06)	0.12	(0.04)	(0.05)	0.426
Hip power generation loading response (W/kg · m)	0.57	(0.30)	(0.34)	0.43	(0.21)	(0.26)	0.008*
Hip power absorption (W/kg · m)	0.45	(0.19)	(0.23)	0.44	(0.16)	(0.20)	0.636
Hip power generation pre-swing (W/kg · m)	0.94	(0.26)	(0.31)	0.88	(0.26)	(0.32)	0.221
Knee extension moment initial contact (N · m/Kg · m)	0.09	(0.03)	(0.05)	0.11	(0.03)	(0.05)	0.010*
Knee flexion moment loading response (N · m/Kg · m)	0.37	(0.13)	(0.15)	0.34	(0.14)	(0.16)	0.236
Knee extension moment terminal stance (N · m/Kg · m)	0.14	(0.06)	(0.08)	0.16	(0.07)	(0.09)	0.156
Knee flexion moment pre-swing (N · m/Kg · m)	0.29	(0.07)	(0.09)	0.23	(0.08)	(0.09)	<0.001†
Knee power absorption loading response (W/kg · m)	0.35	(0.20)	(0.26)	0.33	(0.21)	(0.24)	0.662
Knee power generation mid stance (W/kg · m)	0.46	(0.25)	(0.29)	0.41	(0.16)	(0.19)	0.196
Knee power absorption pre-swing (W/kg · m)	1.43	(0.46)	(0.54)	1.12	(0.43)	(0.51)	0.001†
Ankle plantar flexion moment (N · m/Kg · m)	0.09	(0.03)	(0.04)	0.08	(0.03)	(0.04)	0.062
Ankle dorsiflexion moment (N · m/Kg · m)	0.78	(0.07)	(0.08)	0.80	(0.07)	(0.09)	0.126
Ankle power absorption (W/kg · m)	0.38	(0.12)	(0.18)	0.36	(0.09)	(0.15)	0.417
Ankle power generation pre-swing (W/kg · m)	2.19	(0.48)	(0.58)	1.96	(0.32)	(0.43)	0.005*

* Statistically significant difference at $P < 0.05/27 = 0.0019$.

† Near significant difference at $0.0019 < P < 0.05$.

RESULTS

The age, weight, height, demographics, and mean temporal parameters are listed in Table 3. Both the intersubject standard deviation and total standard deviation for each trial are listed. Cadence was significantly greater in females compared with males. Stride length was also less in females, although when normalized for height, was greater in females. There was no significant difference in velocity.

The kinematic and kinetic joint data for each joint, averaged for all males and females over a full gait cycle, are graphically displayed in Figure 1. Visual inspection of these graphs reveals similar basic

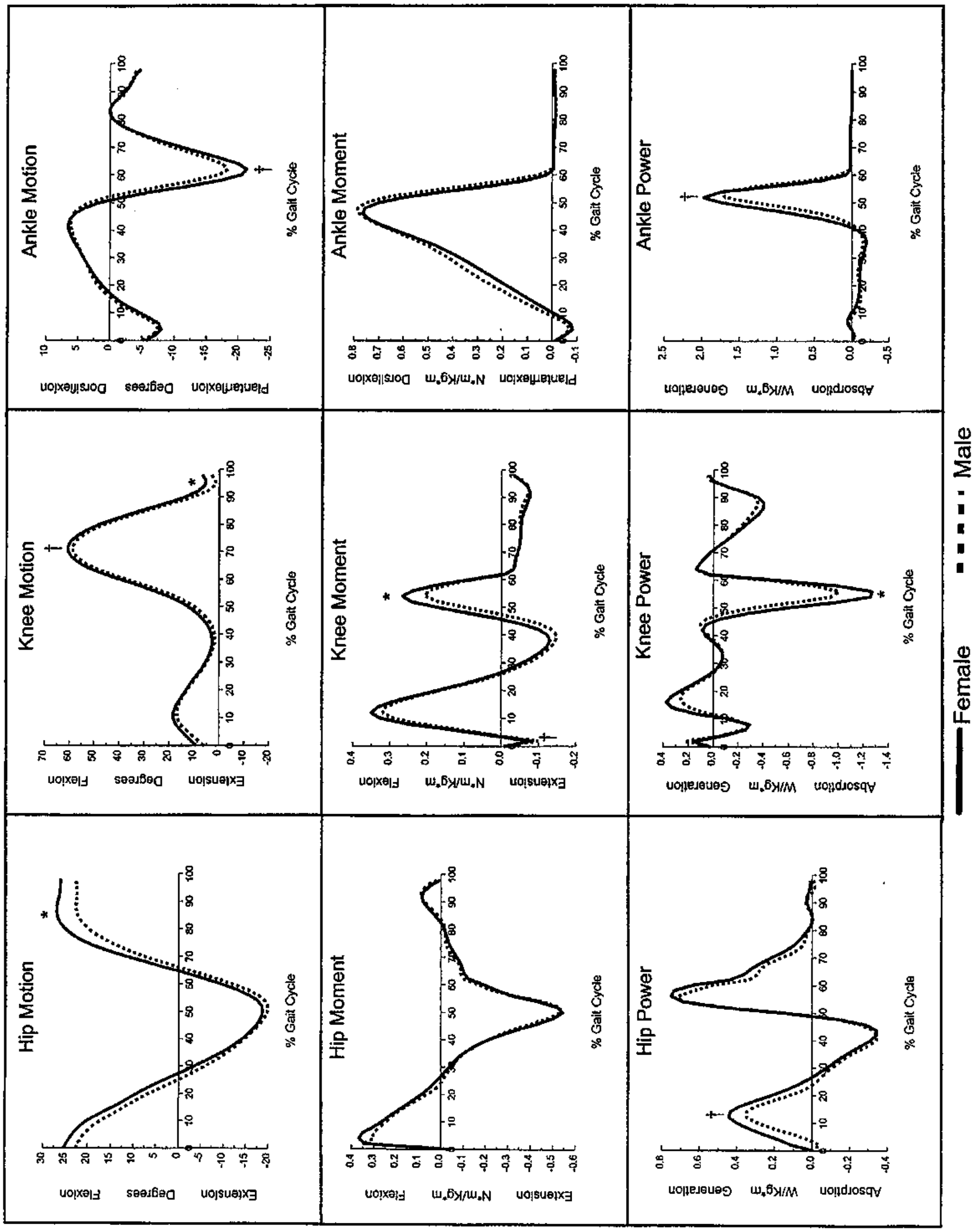

Figure 1. Male *v* female gait: sagittal plan angles, moments, and powers at the hip, knee, and ankle. Gait cycle begins with initial contact at 0%.

TABLE 3

Subject demographics and temporal parameters

	Females			Males			P Values
	Mean	Intersubject (SD)	Total (SD)	Mean	Intersubject (SD)	Total (SD)	
Demographics							
Age (yr)	28.60	(4.50)	—	28.40	(5.00)	—	0.810
Weight (kg)	59.84	(8.08)	—	72.70	(10.34)	—	<0.001*
Height (m)	1.64	(0.07)	—	1.78	(0.06)	—	<0.001*
Temporal parameters							
Cadence (steps/min)	120.40	(9.50)	(10.0)	112.80	(8.50)	(9.00)	<0.001*
Stride length (m)	1.33	(0.10)	(0.10)	1.38	(0.12)	(0.12)	0.029*
Stride length (normalized for height)	0.81	(0.05)	(0.06)	0.78	(0.06)	(0.07)	<0.001*
Velocity (m/s)	1.34	(0.17)	(0.17)	1.30	(0.17)	(0.17)	0.265
Step width (m)	0.12	(0.03)	(0.04)	0.12	(0.04)	(0.05)	0.820

* Statistically significant difference at $P < 0.05$.

patterns between males and females, although several differences in average peak values are apparent. Statistically significantly different peak values are noted with an asterisk (*) and differences with P values greater than 0.0019 and less than 0.05 are noted with a dagger (†). Mean peak values for all kinematic values are listed in Table 1, and mean peak kinetic values are listed in Table 2. Intersubject standard deviations (standard deviations of the subject averages), as well as the overall standard deviations for every trial, are displayed in both tables. Again, statistically significant differences are noted with a an asterisk and differences with P values greater than 0.0019 and less than 0.05 are noted with a dagger.

With respect to kinematic parameters, females had greater peak hip flexion and less knee extension before initial contact. With respect to kinetic parameters, females had greater knee flexion moment in pre-swing and greater peak knee absorption. These differences were all significant at $P < 0.0019$. Additionally, females had a trend toward greater peak knee flexion, ankle plantar flexion, hip power generation in loading response, knee extension moment at initial contact, and greater ankle power generation in pre-swing, all at $0.0019 < P < 0.05$.

DISCUSSION

This is the largest study to date evaluating joint biomechanics within an adult population. Overall, the kinematic and kinetic joint patterns are similar between genders, and we conclude that there are more similarities than differences in gait kinematics and kinetics between males and females. However, we found statistically significant differences when accounting for multiple comparisons in 4 of 27 peak kinematic and kinetic variables. When not accounting for multiple comparisons, statistically significant differences ($P < 0.05$) were observed in an additional 5 of 27 variables.

Females demonstrate significantly greater hip flexion and less knee extension before initial contact, greater knee flexion moment in pre-swing, and greater peak mechanical joint power absorption at the knee in pre-swing. The greater hip flexion in females could be a result of a greater stride length in proportion to height, because peak hip flexion directly correlates with stride length.[14, 15] It is important to note that all kinematic comparisons were made using subjects' individual joint angle positions during quiet standing as the reference point. We did not observe any gender differences in absolute standing hip, knee, or ankle angle. Therefore, our findings of increased hip flexion and reduced knee extension before initial contact in females reflect truly dynamic as opposed to standing offset differences.

The increased overall hip flexion may also be related to the tendency in females toward greater hip power generation in loading response ($P = 0.008$). The proportionally greater stride length does not, however, directly account for the decreased knee extension before initial contact; intuitively, we would expect greater knee extension before initial contact as a means to increase stride length. This finding may point to an intrinsic gender difference in walking dynamics. Females also display greater knee flexion moment and knee power absorption in pre-swing. These knee findings are consistent with a tendency for greater knee flexion in swing for females ($P < 0.036$). Finally, there is a tendency in females toward greater ankle power generation at pre-swing ($P = 0.005$), which may be related to a tendency toward greater peak ankle plantar flexion ($P = 0.014$).

The tendency toward higher peak joint powers in females implies a tendency toward greater mechanical work in joints and surrounding muscles as well.[5, 33] Because females walk at higher cadences compared with males, females also perform greater mechanical work (normalized for height and weight) per unit time and unit distance. The reason for a tendency toward greater powers in females is unclear but may be attributable to the fact that females walk at greater cadences compared with males. A higher cadence would necessitate each joint moving through its range at a faster rate, thereby directly increasing the power generated or absorbed about the joint. Causality, however, may be the opposite; i.e., it may be that greater joint powers in females allow for greater cadences. Finally, these gender differences may not even be based on inherent dynamic differences but, rather, on some unknown, possibly aesthetic factors.[34]

The absolute values of our averaged temporal, kinematic, and kinetic values are largely in agreement with comparable values previously reported in the literature,[5, 9, 14, 15, 23-25, 32, 33, 35] although detailed comparisons are difficult given various differences in protocols, equipment, and measured variables. Because the present study is the largest biomechanical study to date in adults, it may serve as the best biomechanical reference for this age group, both in clinical and research studies. We suggest, however, that individual gait laboratories develop their own databases for reference, as different gait analysis systems and protocols will generate slightly different values. Moreover, because this study demonstrates statistically significant gender differences for several biomechanical gait parameters, we recommend that each laboratory develop separate databases for males and females and that comparative biomechanical evaluations are gender-specific. Future studies will be needed to determine the clinical relevance of these statistically significant differences.

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