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Gender differences in ankle kinematics of adults during gait

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Summary. The ankle plays an important role in human locomotion, because its range of motion is necessary to balance the body during walking, for both genders. However, little information exists on sex-based variations in ankle joint kinematics of adults during the stance phase of gait. The purpose of this study is to evaluate gender differences in ankle kinematics during the stance phase of gait. One hundred and three participants (53 males and 50 females) were enrolled in the study. Seven retro-reflective targets were applied on the skin of their right foot and seven smartphone cameras were used to capture videos. A self-calibration method, which used a photogrammetric bundle adjustment technique, determined the ankle coordinates. The results showed that females have a significantly greater range of ankle motion than males in the transverse plane throughout the stance phase, and that the maximum mean angle of adduction in the heel strike phase for males is greater than for females. The maximum mean angle of inversion/eversion rotation of the ankle for females and males is closer. The results could contribute to the formulation of the diagnosis, through the observation of clinical conditions, and therefore to the determination of the indications for operative treatments for both genders.

Keywords. Ankle, kinematics, range of motion, gender.

Introduction

The ankle plays an important role in standing, walking and other activities.[1-3] An evaluation of the range of motion (ROM) of the ankle is required in footwear design and manufacture. Inappropriate footwear increases discomfort due to deformation from poor posture and to the risk of foot problems, such as bunions, ankle injuries, and chronic foot pain.[4,5] It also plays a part in identifying forensic and medical problems, and acute or chronic injuries in athletes.[6-9] Furthermore, the evaluation of ankle motion during walking is essential to develop the production of foot orthoses within the management of foot and ankle disorders.[10] The limitation of the ankle joint or talocrural (i.e., the joint between the talus and the tibia) ROM affects many aspects of function and balance.[11] The measurement of ankle motion depends on the ankle joint and the transverse tarsal and subtalar joints.[12,13]

In motion, three cardinal planes (coronal, sagittal and transverse) are important.[12] Ankle motions within the coronal plane are inversion (IV) and eversion (EV); in the sagittal plane they are dorsiflexion (DF/upward) and plantar flexion (PF/downward); and in the transverse plane they are adduction (AD), or internal rotation, and abduction (AB), or external rotation of the foot. Combinations of these motions across both the subtalar and tibiotalar joints create three-dimensional motions called supination and pronation.[12,14] The ankle focuses primarily on PF and DF. Movement of the DF and PF is necessary for the strategical balance, in order to decrease the risk of falling.[15] Moreover, the ankle IV and EV ROMs have also been found to be significantly associated with balance and functional test performance.[16] Based on a previous study, the stance phase was defined as heel strike (HS), loading response (LR), mid-stance (MS) and terminal stance/heel off (HO).[17,18] The ankle joint movement is of great importance, as it allows shock absorption on initial contact with the floor, or heel strike, and provides the forward propulsion force during the terminal stance phase.

A variety of devices have been used to quantify ankle kinematics during static or dynamic conditions, such as simple plastic protractors, universal goniometer and oblique fluoroscope.[3,19-22] Among other geometry solutions, close-range photogrammetry (CRP) is a reliable and commonly used technique to measure ankle kinematics, because it is a non-invasive, highly accurate and low-cost tool.[23] For these reasons, it has been used in this study.

Gender is one influential factor that may change ankle ROM during gait. Brockett and Chapman (2016) compared gender differences, and demonstrated that younger females have a higher ankle ROM compared to males.[14] Murray et al. (1985) indicated that there are minimal differences in ROM between females and males.[24] However, there are very few studies regarding ROM in the ankle which evaluate the differences in males and females during gait in adults.[25,26] Thus, the purpose of the present study was to evaluate ankle kinematics during the stance phase gait according to gender in adults.

Methods

Subjects

One hundred and three foot-healthy participants (53 males aged 28-47, with a BMI ranging from 21.54 to 35.85 kg/m^2 and 50 females aged 25-46, with a BMI ranging from 18.93 to 30.48 kg/m^2) participated in this study. Inclusion criteria were as follows: no history of or current injury in the foot and ankle, and no visible foot abnormality during gait. Table 1 presents the basic demographics of the subjects. This study has been approved by the University of Southern Queensland with reference number H18REA168. Every participant was provided with a written consent to be signed prior to their participation in this study.

Foot markers and software

The markers on the body surface are important for shape and motion analysis, because the particular shape of the markers often reflects the underlying structures in the ankle region.[27] The ankle joint axis is close to a mediolateral axis through the ankle joint complex. All axes are close to parallel to the bimalleolar axis.[28] Based on previous studies,[19,20,25,29] seven anatomical locations were identified on the right foot, and 2-mm-diameter self-adhesive stickers were placed on various locations. Table 2 explains these markers and Figure 1 illustrates the locations of the markers.

CRP techniques were used and the subjects' feet were recorded by smartphone cameras during gait. Three-dimensional (3D) coordinates of the foot markers were collected with a video recording. To convert the video frames to images for measurement, Virtual Dub software (v 1.6.15) was used. Data analysis three-dimensional marker positions were calculated using iWitnessPRO-V4 Photometrix software (2018) and the smartphone cameras were calibrated to avoid errors from lens distortion and to determine foot coordinates by using a bundle adjustment technique. MATLAB software calculated the angle created by each of three markers in the coordinate system using the dot product of two vectors. Microsoft Excel software and SPSS version 25 for Windows (IBM Company) were used to analyze data and conduct each statistical analysis.

Experimental procedure

Seven 2-mm-diameter reference points were used on the right bare foot for further analysis.[30,31] The subject placed the subtalar joint in a neutral position (relaxed state) and then markers were mounted on anatomical locations (Table 2). The subject was standing during the 10 seconds required to obtain the digital image, to ensure that their feet were in a neutral posture (the ankle joint at neutral flexion). The ankle centre of rotation was approximated as the midpoint between the tip of the medial malleolus (MM) and the tip of the lateral malleolus (LM) for dorsiflexion-plantar flexion (DP) and external-internal rotation (EI). The approximation is also valid for inversion-eversion (IE) at ankle neutral position when DP, IE, and EI angles are all zero.[32] Then, subjects walked down a 14-m walkway; 7-smartphones were placed about halfway of the walkway, and self-selected walking speed was recorded using them; 4-calibrated boards and retro-reflective markers were determined using the self-calibration bundle adjustment digitized

Table 1. Demographic data of participating subject values are presented as mean (range)

Variable	Male	Female
Demographic measurement		
Age (yr)	37 (28-47)	37 (25-46)
Height (cm)	175.72 (162-185)	160.67 (154-167)
Weight (kg)	89.90 (69.8-119.3)	64.89 (48.7-77.9)
Body mass index (kg/m^2)	29.12 (21.54-35.85)	25.26 (18.93-30.48)
Foot measurement		
Foot length (cm)	26.01 (24-28)	22.39 (20.9-24)
Foot width (cm)	10.08 (9-12)	8.87 (8-10)

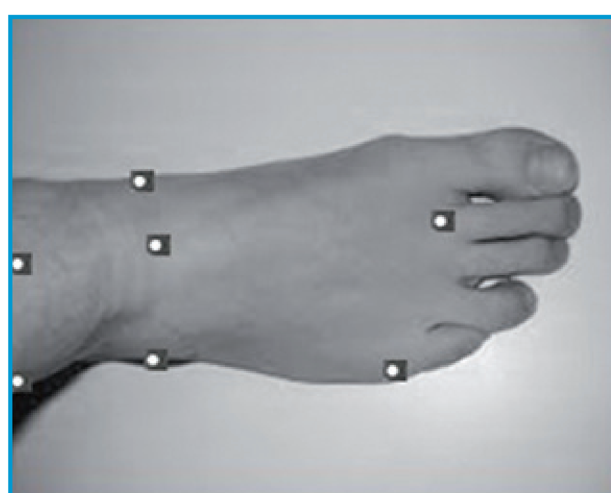

Figure 1. Seven-markers mounted on the right lower shank.

Table 2. Specifics of seven markers and locations

No.	Definitions of landmarks	Location
1	The fifth metatarsophalangeal joints (MPJ), lateral MPJ (LMPJ)	The fifth metatarsal on the lateral side of the foot
2	Lateral malleolus (LM)	Tip of the lateral malleolus
3	Medial malleolus (MM)	Tip of the medial malleolus
4	Lateral of the fibula (LF)	15-cm over the lateral malleolus
5	Top of the second MPJ (SMPJ)	On the dorsal aspect of the head of the second metatarsal
6	Inter-malleolar point (ankle joint center) (IM)	Anterior midway between medial malleolus and lateral malleolus
7	Anterior shank (AS)	15-cm tibia anterior aspect from the inter-malleolar point

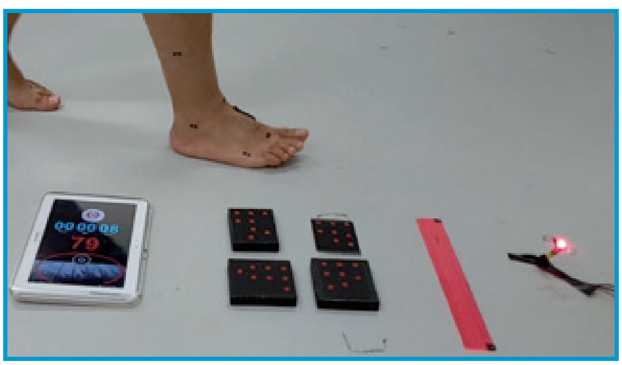

Figure 2. Timer, flash of a LED, scale bar, ruler and 4-calibrated boards for synchronization and accurate calibration.

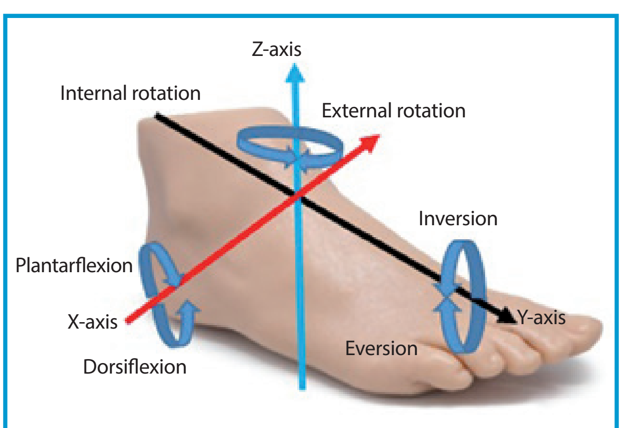

Figure 3. The x-y-z coordinate to describe a screw axis orientation of the ankle. The x-axis was oriented plantarflexion and dorsiflexion (PF&DF), the y-axis inversion and eversion (IN&EV), and the z-axis adduction and abduction (AD&AB).

points (circles) used to calculate the axis-coordinate for all markers. Calibration was performed to reduce any measurement error, and smartphone accuracy testing was carried out before using the devices on the subjects.[33] A timing clock and the flash of a LED was used at 30 second intervals; each flash lasted 0.050 seconds, to synchronize with the video clips. To evaluate the accuracy of each calibration procedure, the measured calibrated length of the scale bar (48.6 mm in length) and ruler were compared to the true length (Figure 2).

Dorsiflexion and plantar flexion angle were defined as the angle created by the line from lateral of the fibula - LF to LM (A) and the line from LM to lateral metatarsophalangeal joints - LMPJ (B).[34] Eversion and inversion angles were created by the line from anterior shank - AS to inter-malleolar point - IM (A) and the line from LM to MM during IM (B).[35] The line from LM to MM (A) and IM to SMPJ (B) created internal-external rotation angles. For this investigation, an X-Y-Z Cardan sequence was applied. This describes sagittal plane motion around an x-axis, coronal plane motion around a y-axis, and transverse plane motion around a z-axis. This is similar to what described by Grood and Suntay (1983).[36] Information from the International Society of Biomechanics (ISB) was used to describe motions of the ankle and subtalar joints. As a result, rotation in the sagittal plane (y-z plane) was defined as dorsiplantarflexion, in the coronal plane (x-z plane) as inversion-eversion, and in the transverse plane (x-y plane) as internal-external rotations[29] (Figure 3).

In the present study, the change in the position and orientation of the ankle bone angles of each triplane for each of the stance phases (HS, LR, MS, and HO) from the neutral posture was quantified. The rotational angles around the x, y and z axes represent dorsiflexion (+)/plantarflexion (-), inversion (+)/eversion (-) and internal (+)/external (-) rotation, respectively, according to ISB's definitions. The angles were calculated in a manner similar to the method used by Tome et al., (2006), using Eq.1.[37]

$$\text{MLA angle} = \cos^{-1} \frac{\vec{A} \cdot \vec{B}}{|A||B|} \ \dots (1)$$

Statistical analysis

Data processing and analysis used SPSS version 25 for Windows (IBM Company). Descriptive analysis used mean and standard deviation for general characteristics. The independent Levene's test to measure significant differences of ankle ROM between genders (statistical significance level) was less than 0.05 in P-value. Intraclass correlation coefficient (ICC) is a widely used reliability index in intra-sessions, therefore 3-sessions measured the three cardinal planes angles in four phases in stance phase during gait for all participants.

Results

Fifty-three males and fifty females participated in this study. The mean, standard deviation and mean differences for ROM of the ankle were computed (Table 3). Levene's test for equality of variances and independent sample t-tests were performed to evaluate any differences between genders for the ankle kinematic angles, with p <0.05 considered significant. The results of this study demonstrated significant differences between females and males for the transverse plane of ROM of the ankle (F = 12.21, Sig = 0.013 and 95% confidence interval of the differences between -5.312 and 1.587). However, no significant differences of coronal and sagittal planes were found between males and females.

The ICC, lower and upper bound, and standard error of measurement (SEM) data of triplanar angles of the ankle during stance phase for three sessions of both genders are presented in Table 4. The average of ICC for the triplanar during stance phase was 0.89 for males and

Table 3. Mean ± SD of triplane angles during stance phase gait for males and females

Plane	Males				Females				Differences			
	HS	LR	MS	HO	HS	LR	MS	HO	HS	LR	MS	HO
Coronal IV(+)/EV(-)	1.15 ±0.39	-4.12 ±0.99	0.84 ±1.14	2.94 ±0.48	0.85 ±0.33	-5.68 ±1.15	0.34 ±0.20	3.17 ±0.22	0.3	-1.56	0.5	-0.23
Sagittal DF(+)/PF(-)	3.20 ±0.59	9.45 ±3.71	2.73 ±2.66	-7.84 ±2.10	3.67 ±0.10	10.93 0.91	7.55 ±1.46	-12.85 ±0.03	-0.47	-1.48	-4.82	-5.01
Transverse AD(+)/AB(-)	2.51 ±1.41	2.13 ±1.56	2.56 ±0.33	1.72 ±0.46	0.72 ±14.71	3.01 ±15.37	7.00 ±17.67	5.64 ±15.31	1.79	-0.88	-3.92	-3.92

SD: standard deviation, HS: heel strike, LR: loading response, MS: mid-stance, HO: heel off, IV: inversion, EV: eversion, DF: dorsiflexion, PF: plantar flexion, AD: adducion, AB: abduction.

Table 4. Mean reliability values between intra-sessions errors for the ankle in gender groups during gait

Stance phase	Plane	Intra-sessions coefficient of correlation and standard error of measurement							
		Males				Females			
		Intraclass correlation	95% confidence interval		SEM	Intraclass correlation	95% confidence interval		SEM
			Lower bound	Upper bound			Lower bound	Upper bound	
HS	coronal	0.85	0.68	0.94	6.67	0.89	0.75	0.96	5.01
	sagittal	0.92	0.83	0.96	2.97	0.98	0.95	0.99	2.30
	transverse	0.86	0.69	0.94	5.88	0.5	-0.17	0.82	10.63
LR	coronal	0.95	0.9	0.98	4.26	0.87	0.7	0.95	7.04
	sagittal	0.94	0.88	0.97	4.87	0.69	0.27	0.88	7.36
	transverse	0.86	0.7	0.94	6.06	0.63	0.13	0.86	7.93
MS	coronal	0.96	0.92	0.98	3.90	0.92	0.83	0.97	4.38
	sagittal	0.98	0.96	0.99	2.37	0.89	0.75	0.96	6.73
	transverse	0.94	0.88	0.97	3.06	0.79	0.51	0.92	2.81
HO	coronal	0.92	0.83	0.96	4.13	0.92	0.82	0.97	4.74
	sagittal	0.94	0.88	0.97	3.69	0.91	0.78	0.96	4.76
	transverse	0.62	0.18	0.84	7.94	0.95	0.89	0.98	2.96

SD: standard deviation, HS: heel strike, LR: loading response, MS: mid-stance, HO: heel off, IV: inversion, EV: eversion, DF: dorsiflexion, PF: plantar flexion, AD: adducion, AB: abduction, SEM: standard error of measurement.

0.83 for females. The overall value of the ICC was 0.86, "Good". Furthermore, the SEM for triplanar angles of the ankle during the stance phase ranged from 2.3 to 9.7 for males and from 2.3 to 10.6 for females; in total, the SEM was approximately 5. To be noted that both the SEM and the ICC are indicative of reliable measures.

Discussion

The aim of this study was to evaluate the ankle kinematics during gait according to the gender of adults. To the best of our knowledge, the current study is the first to evaluate the ankle kinematics during gait using CRP. Motion of the ankle occurs primarily in the sagittal plane, with plantar- and dorsi-flexion occurring predominantly at the tibiotalar joint,[14] but also includes eversion, inversion, and internal and external rotation. The literature describes an overall range of motion in the sagittal plane, from 10 to 20 of DF and 40 to 55 of PF. The ROM in the coronal plane is about 23 IN and 12 EV, while in the transverse plane the ROM is between 5-6 degrees.[38] In our study, the ROM of DF was 4 to 13, and 5 to 13 for PF. In the coronal plane the ankle ROM was approximately 4 to 6 degrees, and in the transverse plane it was between 3 and 23 degrees.

Essentially, the ankle joint begins in a few degrees of dorsiflexion at HS and then rapidly leads to plantar flexes under the control of an eccentric (lengthening) contraction of the ankle dorsiflexors (primarily anterior tibialis), until the foot is flat on the ground. At this stage, the foot is in mid-stance, in order to maintain body balance during the entire gait cycle.[1] At the position with the foot flat, the ankle then begins the process of dorsiflexion. The foot becomes stationary, and the tibia becomes the moving segment. The heel then starts to lift at the beginning of double support, causing a rapid ankle plantar flexion at the terminal of the stance phase.[39,40] In the current study, both genders' ankle joint motion was slightly dorsiflexed on HS. After heel contact, the ankle rapidly dorsiflexes to a maximum of 13 degrees, just prior to MS. The ankle then plantar flexes progressively, reaching a maximum PF of 13 until HO. A small range of IN in the coronal plane on HS then moves gradually to EV until MS increases slightly to IN on HO. In the transverse plane, all stance phases were AD in both genders. Overall, females had a greater ROM of ankle planes during the stance phase, with the exception of the beginning-of-walking (HS) values, when males had values converging with females' (Figure 4).

In females, the transverse plane of ROM of the ankle was significantly larger in the stance phase of gait (Sig = 0.013), compared with males. However, there were no significant differences between genders in relation to ankle joints of ROM in sagittal and coronal planes. Since females tend to have more ligamentous laxity than males,[41] females are thought to have better flexibility than males in the ankle joint, causing them to have larger ankle ROM than males. Actually, many previous studies report that females have larger ankle ROM than males[2,24,42] and the outcomes of our study are therefore consistent with these studies. In addition, females have smaller bone dimensions and are predisposed to lower bone density. These factors increase the high rates of ankle injury and the risk of broken bones. Furthermore, in order to minimize the risk of falls and to prevent ankle injury, it is essential to confirm the differences of balance with low extremities according to ROM between females and males. Murray et al. (1985) established that there are minimal differences of ROM between females and males. The ROM during stance was greatest for DP in both gender and least for EI in males.[24] The findings

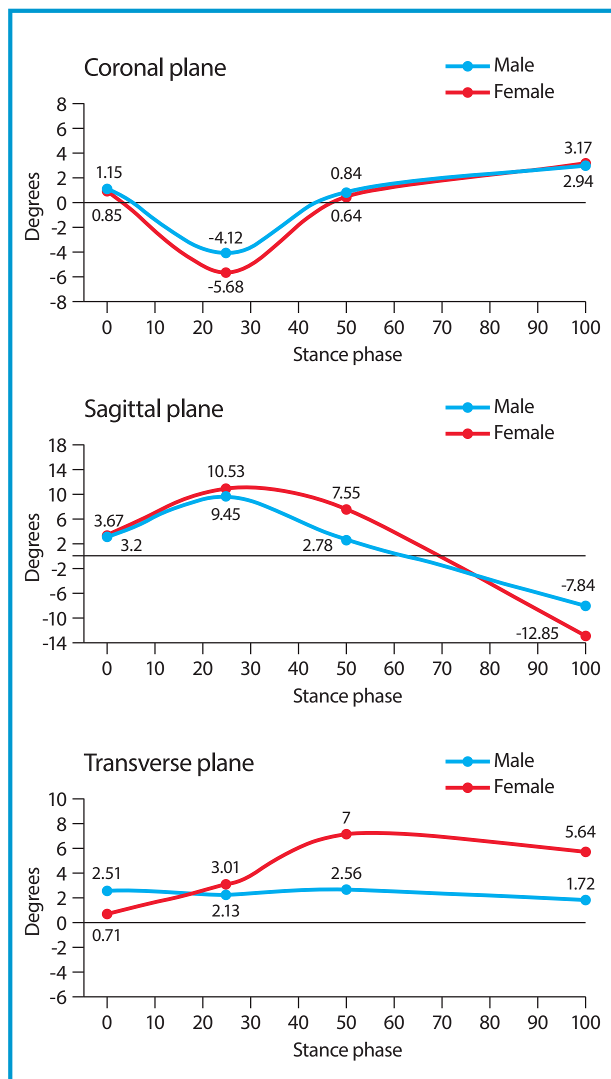

Figure 4. Ankle kinematics during stance phase gait for males and females.

in our results were consistent with the study conducted by Murray et al. (1985).

It is important to determine whether there are gender differences in musculoskeletal injury rates, such as ankle sprains and stress fractures while walking or running, two injuries that are considered more serious than other types of ankle disease. Fifty percent of the increased risk of ankle sprains is associated with the lack of joint stability or laxity ankle ROM. In our study, females have more joint laxity ankle ROM. Therefore, they are more likely to suffer from ankle sprains than males. Nonetheless, more research is needed on this topic to develop a consensus on ankle injury risk factors.

It is estimated that changes in gait pattern are related with increased age. In ROM, there is an inverse correlation between the decrease in muscle strength and increased age. Several studies reported that older adult walk at slower speeds than younger adults, with shorter step length, being therefore more likely to fall.[43]

Reliability determination is essential for validity. The acceptable intraclass reliability was determined through analysis from three testing sessions focusing on the reliability of ankle kinematics. Reliability mean value between intra-sessions was 0.83 for the female group and 0.89 for the male group. The composite measure of ankle kinematics results demonstrates good reliability (ICC = 0.86) compared with Konor et al. (2012), which had good reliability (ICC >0.85) when measured with the goniometer technique.[44]

However, the present study has some limitations that need to be addressed in future studies. First, the sample size included only 103 adult subjects from Middle Eastern countries. Second, the study used surface markers, and since skin markers do not precisely reflect the underlying bones, the results may be inaccurate.

Conclusions

In conclusion, this study demonstrates the gender difference of ankle ROM. Specifically, our results show that females have more joint laxity and flexible ankle ROM than males and males have a higher ROM of AD in the HS phase; therefore, it is necessary to assess and plan the training program for ankle ROM in males. Further research is needed to ascertain the most effective way to improve ankle joint flexibility in males; this would be beneficial for the prevention of falls, especially among the elderly. These results may contribute to the effectiveness of understanding gender differences in ankle function, and may be useful to understand and treat ankle joint conditions in a gender-specific method. In the future, the authors will commit to developing this study further to include a larger sample and compute the three planes of other segments at the lower extremity of the body.

Key messages

- Gender differences exist in ankle kinematics. Compared with male, female show a greater range of ankle motion in the transverse plane.
- Males have higher angle adduction in the heel strike than females.
- In adults, the angle of inversion/eversion rotation of the ankle is similar in females and males.
- The close-range photogrammetry (CRP) technique could be successful to evaluate the body and the foot during gait.

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