COMPARISON BETWEEN MALE AND FEMALE GAIT MODES PART I: KINEMATICS OF THE ANKLE, KNEE AND HIP JOINTS

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Abstract: *The differences between male and female locomotion pattern can be observed in nature. This article uses the Karhunem-Loève decomposition (KL) to establish the common kinematics gait modes of motion of the ankle, knee and hip joints. This study was undertaken to demonstrate the differences between male and female kinematics variables. The results were obtained through the analysis of 24 male and 33 female healthy subjects. The system VICON 140 was used for motion data acquisition. The frequency of this equipment was set in 60 Hz. The main kinematics differences between male and female groups were identified.*

Keywords: Gait Modes, Gait analysis, Human Locomotion, Karhunem-Loève Decomposition, Kinematics.

1. Introduction

Walking and running are the most common human movements and probably the most complex. The individual walking pattern is a personal identity because each of us performs a characteristic and unique way of walking (Winter, 1991). The greater number of degrees of freedom, the action of a lot of muscles across the joints and the variability of the kinematics chain, which changes between support (close chain) and swing (open chain), are some of the factors that influence the human locomotion.

The human gait maturation involves the central nervous system (CNS) maturation and the musculoskeletal growth (Vaughan *et al*., 1997). Children acquire the ability to walk without support between 12 and 15 months of life, and to run at 18 months (Sutherland *et al*., 1980). After this period, the CNS and musculoskeletal system maturation will define the personal gait pattern, such as: frequency, length and width of steps, among others.

During the past years, some researchers have been using the KL in the study of spatiotemporal systems. Deluzio *et al*. (1997) analyzed 29 asymptomatic elderly subjects and 13 patients to describe knee joint kinematics and kinetics as measurement by the three principal components (PCs) of the bone-on-bone forces, net reaction moments and relative knee angles. The patients were submitted to pre-operative and one-year post-operative gait analysis, and received unicompartmental arthroplasties. Through these PCs, Deluzio could detect which gait measurements were abnormal as well as the interpretation of the gait cycle responsible for the differences. Shutte *et al.* (2000) applied the KL technique to derive a set of 16 independent parameters from selected kinematics gait data and interpreted the sum of the square of these 16 independent variables as the deviation of subject’s gait from normal. In this study, 24 normal subjects were used to define the normal pattern and 71 patients with a diagnosis of cerebral palsy were analyzed. Sadeghi *et al.* (2000) demonstrated how the KL analysis can be applied to detect the main functional structure of actions taken by hip extensors and flexors of able-bodied subjects, and to determine whether or not symmetrical behavior between right and left hip muscle power activity exists. Sadeghi analyzed 20 young, healthy male subjects and applied the KL as a classification and curve structure detection method to hip sagittal muscle power calculated for the right and left lower limbs. Over 70% of the information was captured by the first four principal components and the existence of functional asymmetry in gait was detected.

The aim of this work is to study the differences between male and female Brazilian subjects and present an application of the gait modes as an alternative way to investigate kinematics differences. These gait modes were obtained from the Karhunem-Loève decomposition (KL), also know as Principal Component Analysis (PCA).

2. Methods

The methodology adopted in this work involves many phases, as: the mechanical modeling of the human lower limbs (Raptopoulos, 2003), determination of the male and female control groups, definition of the experimental protocol, kinematics analysis of the data, determination of the gait modes by the Karhunem-Loève decomposition approach and statistical analysis of the results.

2.1. KL-Transform

The kinematics gait data can be represented as a set of time functions of some chosen parameters or coordinates. The KL is able to decompose this spatiotemporal data set into time-independent spatial structures and corresponding time-dependent scalar amplitudes. At the same time this method indicates the relative importance of each spatial structure in retaining the original information contained in the data set.

The KL analysis as a modal decomposition method was applied to the ankle, knee and hip relative angles of 24 male and 33 female normal young volunteers. First, the data matrixes D_m (1) and D_f (2) for each specific male m ($m = 1..24$) and female f ($f = 1..33$) volunteer, were assembled. These matrixes have 101 rows (1), corresponding to the time duration (0-100%) of the gait cycle, and 9 columns that are related to the kinematics variables observed (sagittal, frontal and transverse angles of ankle, knee and hip joints, respectively).

$$D_m = \begin{bmatrix} & | & | & \\ ankle & | & knee & | & hip \\ (101x3) & | & (101x3) & | & (101x3) \\ & | & | & \end{bmatrix}_{101x9} \qquad m = 1..24 \tag{1}$$

$$D_f = \begin{bmatrix} & | & | & \\ ankle & | & knee & | & hip \\ (101x3) & | & (101x3) & | & (101x3) \\ & | & | & \end{bmatrix}_{101x9} \qquad f = 1..33 \tag{2}$$

Second, in order to perform the KL, the mean values $\overline{D}_{mj}$ and $\overline{D}_{fj}$, which represent the average angular displacement of each column j of male and female matrixes, were subtracted from the elements $\overline{D}_{mj}$ and $\overline{D}_{fj}$, giving the new matrixes W_m (3) and W_f (4).

$$W_{mij} = D_{mij} - \overline{D}_{mj} \qquad m = 1..24 \quad i = 1..101 \quad j = 1..9 \tag{3}$$

$$W_{fij} = D_{fij} - \overline{D}_{fj} \qquad f = 1..33 \quad i = 1..101 \quad j = 1..9 \tag{4}$$

Third, the correlation matrix for each male C_m and female C_f volunteer (dimension 9x9), based in W_m and W_f, respectively, was determined. Through the standard eigenvalue problem, the male (5) and female (6) eigenvalues (λ_{mj}, λ_{fj}) and eigenvectors (q_{mj}, q_{fj}) of each correlation matrix were obtained. The eigenvalues represent the extreme values of the variance of the data while the eigenvectors can be understood as *gait modes* of walking, with specific time varying amplitudes. The relative importance of each *gait mode* representing the whole motion is assessed by the eigenvalues.

$$C_m.q_{mj} = \lambda_{mj}.q_{mj} \qquad m = 1..24 \qquad j = 1..9 \tag{5}$$

$$C_f.q_{fj} = \lambda_{fj}.q_{fj} \qquad f = 1..33 \qquad j = 1..9 \tag{6}$$

Fourth, the male a_{mj} and female a_{fj} time-dependent amplitude functions were determined by the projection of the matrixes W_m and W_f into the corresponding eigenvector q_{mj} and q_{fj}, respectively. Fifth, if the space of eigenvectors is extended to include the average male $q_{m0} = \overline{D}_{mj}$ and female $q_{f0} = \overline{D}_{fj}$ eigenvectors, and the male and female amplitude function $a_{m0} = a_{f0} = 1$ is considered constant for every instant of time, the original data set D_m (7) and D_f (8) can be obtained,

$$D_m = \sum_{j=0}^{n} a_{mj}.q_{mj} \qquad m = 1..24 \qquad j = 1..n \qquad n = 9, \tag{7}$$

$$D_f = \sum_{j=0}^{n} a_{fj}.q_{fj} \qquad f = 1..33 \qquad j = 1..n \qquad n = 9 \tag{8}$$

where $n = 9$ represents the total number of kinematics variables (columns of the matrixes D_m and D_f). Finally, it is possible to approximate the original data using fewer eigenvectors than n restricting the summation over l (7, 8). Assuming that the male $\lambda_{m1},...,\lambda_{ml}$ and female $\lambda_{f1},...,\lambda_{fl}$ eigenvalues are ordered from the greatest value to the smallest one truncating the series after l terms, the result is an approximation D_m^* (9) and D_f^* (10) of the original data.

$$D_m^* = \sum_{j=0}^{l} a_{mj}.q_{mj} \qquad m = 1..24 \qquad l < n \tag{9}$$

$$D_f^* = \sum_{j=0}^{l} a_{fj}.q_{fj} \qquad f = 1..33 \qquad l < n \tag{10}$$

This analysis is valid for a single gait or a group of volunteers. The aim of this work is to find the similarities of these gait modes in a group of 24 male and 33 female healthy volunteers, repeating this procedure for each of them and comparing the results.

2.2. Experimental Protocol

The motion analysis was performed by using a computer-aided video motion analysis system with three infrared cameras (VICON 140) synchronized to two Bertec Co. force plates. The signal was filtered by a fourth-order Butterworth low pass filter with video cut-off frequency of 6 Hz and force plate cut-off frequency of 30 Hz. The position of the markers' was used in the inverse kinematics approach (Raptopoulos, 2003) to calculate the relative angle of joints in the sagittal, frontal and transverse planes. The hip center of rotation was estimated through regression equations (Bell *et al*., 1989; Seidel *et al*., 1995; Leardini *et al*., 1999).

Fifty-seven healthy and young volunteers participated in this work, being: thirty-three female and twenty-four male. They had no previous history of surgery or musculoskeletal problems that could affect their walking pattern. They were asked to walk at their normal cadence. The male group presented an average and standard deviation age of 22.64 ± 2.32 years and cadence of 97.49 ± 9.20 steps/minute; while the female group presented an average and standard deviation age of 21.91 ± 1.51 years and cadence of 104.10 ± 7.25 steps/minute.

3. Results and Discussion

3.1. Gait analysis

The angular displacements obtained from the gait analysis of the male and female control groups are presented (Fig. 1). Some of these results are presented during the total gait cycle while others are presented only during the support phase. This was done because some frontal and transverse joint rotations are very small during the swing phase and do not have greater importance for gait analysis (frontal knee angular displacements, for example). The angular displacements and spatiotemporal parameters are in agreement with those presented in literature (Winter, 1991; Raptopoulos, 2003).

The mean values for knee angle in the frontal and transverse planes were very small (Fig. 1e). These results are normal for healthy subjects. The female abduction posture in relation to the male adduction posture is expected. In the transverse plane the internal and external rotations of these groups were very small too. This is a normal condition because, during the support, the knee is locked and cannot rotate around its longitudinal axis. It is important to observe that these small values represent only a mean and can be strongly influenced by the skin movements, markers position and system error.

The Anderson-Darling Test was applied to observe the hypothesis of a normal distribution. The T test was applied in order to confirm the null hypothesis that there are not differences between the groups (H0 = means are equals) with the alternative hypothesis that there are differences between the groups (H1 = means are not equals). A significance level of 5.0% was adopted, so p-valor greater than 0.05 indicates that there are no differences between the groups. The T test was applied to the kinematics angular displacements in the initial contact (phase 1), load response (phase 2), pre-swing (phase 3), support phase (phase 4) and middle swing (phase 5). The analysis of the ankle, knee and hip angles are shown in Tables 2 to 4, respectively.

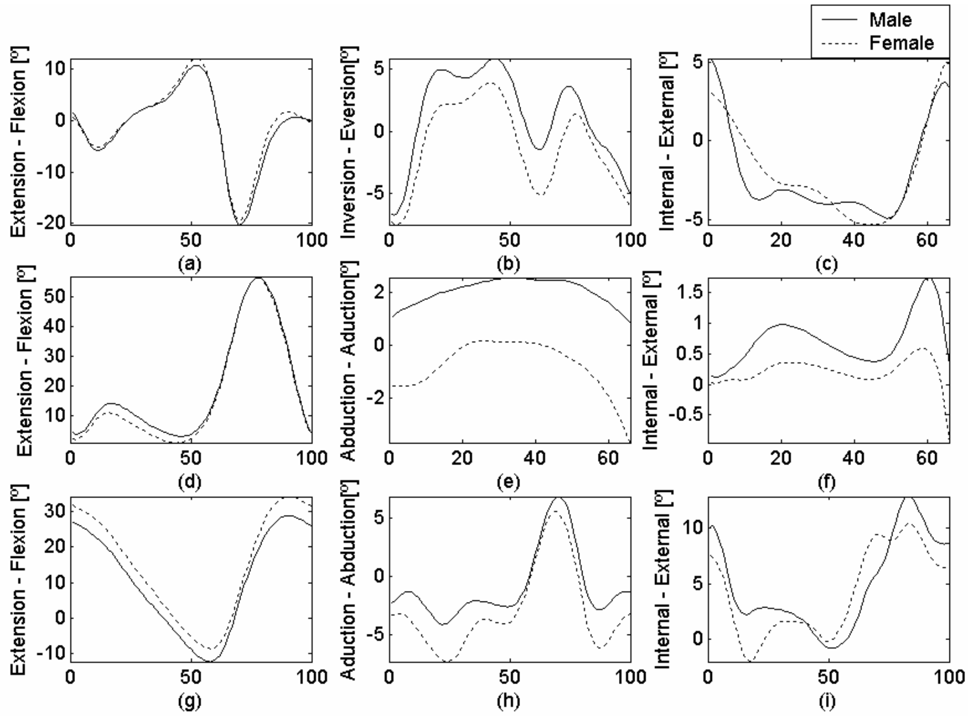

Figure 1. Kinematics of the ankle, knee and hip joints in the sagittal (a, d, g), frontal (b, e, h) and transverse planes (c, f, i). The transverse angle of the ankle, the frontal and transverse angles of the knee are related to the support phase. All the others graphics are related to the total gait cycle.

Table1. Statistical analysis of the ankle kinematics.

Joint	Plane	Phase	Male		Female		T-test p-value	Hypothesis
			Mean [º]	(1) Std [º]	Mean [º]	(1) Std [º]		
Ankle	Sagittal	1	1.56	3.94	0.68	3.05	0.34761	H0
		2	-3.79	3.29	-3.29	2.82	0.54152	H0
		3	10.29	3.18	11.48	3.26	0.17567	H0
		4	-18.74	4.70	-17.99	5.78	0.60487	H0
		5	-2.96	4.47	-0.71	3.91	0.048239	H1✓
	Frontal	1	-6.67	3.17	-7.24	3.82	0.55175	H0
		2	4.14	2.57	0.78	2.44	5.9792e-006	H1✓
		3	4.44	3.38	1.46	3.46	0.0020507	H1✓
		4	1.04	3.76	-3.27	6.28	0.32629	H0
		5	0.04	3.50	-0.80	2.95	0.18601	H0
	Transverse	1	5.22	5.07	3.06	5.00	0.11399	H0
		2	-3.44	4.21	-2.29	3.49	0.26405	H0
		3	-4.89	3.82	-4.91	3.49	0.98575	H0
		4	1.40	4.16	4.25	5.84	0.046015	H1✓
		5	-1.09	4.43	0.98	4.35	0.083249	H0

(1) Std = Standard-deviation.

Through the statistical analysis of the ankle, knee and hip angular displacements the null hypothesis H0 was confirmed or not for a significance level of 5.0%. The ankle had the null hypothesis rejected for: sagittal angle in the middle swing (p = 0.048239), frontal angle in the load response (p = 5.9792e-006) and pre-swing (p = 0.0020507), and transverse angle in the support (p = 0.046015). The knee had the null hypothesis rejected for: sagittal angle in the initial contact (0.011485), sagittal angle in the load response (7.2473e-006), all frontal angles, transverse angle in the load response (0.017109) and middle swing (0.0065909). The hip had the null hypothesis confirmed only for the sagittal angle in the support (p = 0.10056), frontal angle in the initial contact (p = 0.097645), and transverse angle in the pre-swing (0.6181) and middle swing (0.061991).

The greater female frontal amplitude of movement in the hip agrees with the female walking pattern, which presents a perceptive lateral balance, as expected. Another expected result is the major hip flexion of the female group.

Table 2. Statistical analysis of the knee kinematics.

Joint	Plane	Phase	Male		Female		T-test p-value	Hypothesis
			Mean [º]	(3) Std [º]	Mean [º]	(1) Std [º]		
Knee	Sagittal	1	4.18	3.15	2.25	2.43	0.011485	H1✓
		2	14.00	2.75	10.74	2.22	7.2473e-006	H1✓
		3	3.72	2.49	2.13	3.48	0.061223	H0
		4	38.67	4.27	38.58	6.90	0.95257	H0
		5	49.75	3.30	48.83	3.34	0.30819	H0
	Frontal	1	1.10	2.31	-1.56	1.86	1.2048e-005	H1✓
		2	2.08	1.88	-0.40	2.11	2.6559e-005	H1✓
		3	2.39	2.05	-0.53	2.18	3.8362e-006	H1✓
		4	0.63	4.30	-4.20	2.69	2.9075e-006	H1✓
		5	-2.24	4.74	-6.79	2.89	3.6479e-005	H1✓
	Transverse	1	0.15	0.70	0.03	0.43	0.4304	H0
		2	0.93	1.13	0.29	0.83	0.017109	H1✓
		3	0.49	0.64	0.20	0.72	0.11498	H0
		4	-0.57	4.25	-2.21	4.99	0.20051	H0
		5	-4.11	3.87	-7.01	3.80	0.0065909	H1✓

(1) Std = Standard-deviation.

Table 3. Statistical analysis of the hip kinematics.

Joint	Plane	Phase	Male		Female		T-test p-value	Hypothesis
			Mean [º]	(3) Std [º]	Mean [º]	(1) Std [º]		
Hip	Sagittal	1	26.91	5.20	31.77	3.72	0.00012988	H1✓
		2	18.45	5.68	23.29	4.44	0.00065707	H1✓
		3	-8.89	5.86	-5.22	3.99	0.0066614	H1✓
		4	0.04	6.27	2.60	5.26	0.10056	H0
		5	26.30	4.80	31.45	4.43	0.0001054	H1✓
	Frontal	1	-2.31	2.51	-3.35	2.15	0.097645	H0
		2	-3.16	1.86	-6.05	2.23	3.3428e-006	H1✓
		3	-2.60	0.96	-3.94	2.06	0.0045839	H1✓
		4	6.48	1.27	5.50	1.77	0.024555	H1✓
		5	-2.35	2.87	-5.27	3.32	0.0010502	H1✓
	Transverse	1	10.09	4.95	7.50	4.11	0.035879	H1✓
		2	2.31	3.83	-2.00	3.47	4.4446e-005	H1✓
		3	-0.75	3.56	-0.20	4.49	0.6181	H0
		4	5.37	4.44	9.01	5.22	0.0077203	H1✓
		5	12.77	4.66	10.36	4.76	0.061991	H0

(1) Std = Standard-deviation.

3.2. Gait modes

The relative importance of each male and female eigenvalues is presented (Fig.2). The five greatest eigenvalues summed covered 99.6 % of the total variance (information) of the original data.

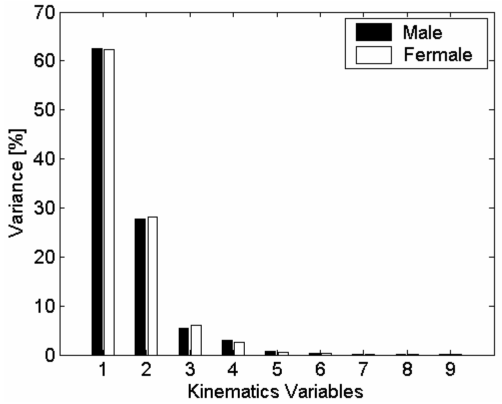

Figure 2. Variances obtained by the kinematics data of the male and female control groups.

The other four eigenvalues were neglected. The five most important eigenvalues are used to choose the eigenvectors or gait modes (Fig. 3). These modes show how each kinematics variable influences the final angular pattern.

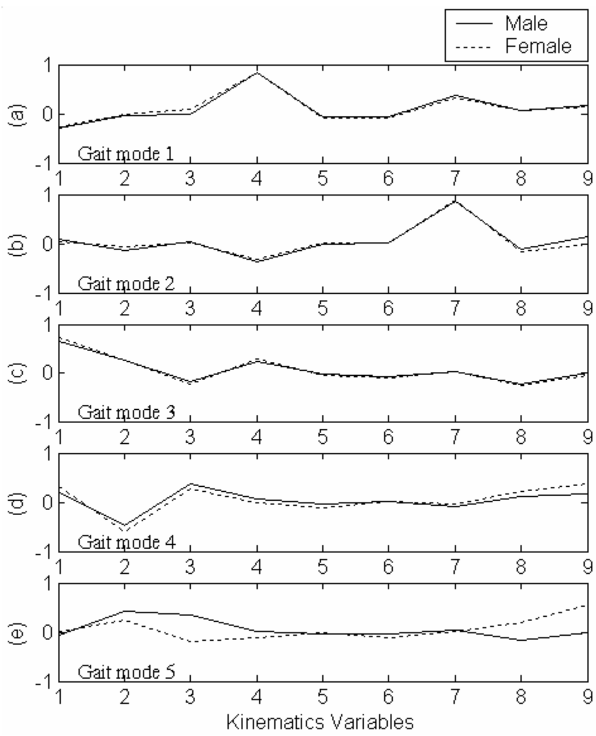

Figure 3. Mean gait modes and individual amplitude functions of the male and female groups of control (five most important gait modes).

The first to third gait modes are very similar and have few differences. The greater differences were identified in the fourth and fifth modes. As in the previous analysis, the Anderson-Darling Test was applied to observe the hypothesis of a normal distribution and the T test was applied in order to confirm or not the null hypothesis that there are no differences between the groups (H0 = means are equals). A significance level of 5.0% was adopted. The T test was applied for the five gait modes, where each mode is composed by nine kinematics variables: (1) sagittal angle of the ankle, (2) frontal angle of the ankle, (3) transverse angle of the ankle, (4) sagittal angle of the knee, (5) frontal angle of the knee, (6) transverse angle of the knee, (7) sagittal angle of the hip, (8) frontal angle of the hip, and (9) transverse angle of the hip. The statistical analysis of these modes is presented in Tab. 4.

Table 4. Statistical analysis of more important gait modes.

		(1)Variables	Male		Female		T-test	Hypothesis
			Mean	Std	Mean	(2)Std	p-value	
Gait Modes	First	1	-0.297	0.067	-0.259	0.093	0.098481	H0
		2	-0.030	0.067	-0.024	0.068	0.72698	H0
		3	-0.015	0.072	0.087	0.047	3.1057e-008	H1✓
		4	0.830	0.047	0.841	0.052	0.42294	H0
		5	-0.064	0.079	-0.100	0.059	0.045316	H1✓
		6	-0.071	0.063	-0.099	0.079	0.14218	H0
		7	0.373	0.105	0.330	0.159	0.25739	H0
		8	0.074	0.042	0.069	0.051	0.70863	H0
		9	0.163	0.059	0.154	0.076	0.60111	H0
	Second	1	0.081	0.121	0.044	0.113	0.2494	H0
		2	-0.136	0.097	-0.071	0.111	0.023485	H1✓
		3	0.042	0.062	0.002	0.080	0.041766	H1✓
		4	-0.368	0.097	-0.315	0.151	0.14398	H0
		5	-0.001	0.040	0.017	0.044	0.10244	H1✓
		6	0.005	0.051	0.014	0.072	0.56984	H0
		7	0.863	0.056	0.890	0.054	0.064108	H0
		8	-0.127	0.077	-0.164	0.064	0.053294	H0
		9	0.147	0.092	-0.001	0.088	9.3479e-008	H1✓
	Third	1	0.638	0.369	0.714	0.270	0.37258	H0
		2	0.249	0.260	0.248	0.246	0.98096	H0
		3	-0.184	0.281	-0.222	0.157	0.52373	H0
		4	0.245	0.144	0.278	0.096	0.30232	H0
		5	-0.024	0.095	-0.045	0.067	0.34002	H0
		6	-0.086	0.103	-0.111	0.087	0.32379	H0
		7	0.031	0.094	0.013	0.097	0.48683	H0
		8	-0.243	0.114	-0.258	0.106	0.61195	H0
		9	-0.001	0.200	-0.048	0.159	0.32733	H0
	Fourth	1	0.192	0.416	0.317	0.299	0.19386	H0
		2	-0.476	0.265	-0.596	0.212	0.065205	H0
		3	0.380	0.421	0.274	0.180	0.20363	H0
		4	0.062	0.148	-0.018	0.100	0.018481	H1✓
		5	-0.047	0.125	-0.103	0.094	0.061143	H0
		6	0.015	0.126	0.005	0.121	0.76199	H0
		7	-0.101	0.116	-0.047	0.103	0.070248	H0
		8	0.111	0.170	0.219	0.164	0.019026	H1✓
		9	0.168	0.205	0.370	0.206	0.00057108	H1✓
	Fifth	1	-0.063	0.183	0.016	0.150	0.077131	H0
		2	0.429	0.213	0.246	0.295	0.011983	H1✓
		3	0.340	0.428	-0.183	0.351	4.9105e-006	H1✓
		4	0.000	0.113	-0.126	0.092	2.1052e-005	H1✓
		5	-0.044	0.148	-0.023	0.171	0.62707	H0
		6	-0.042	0.257	-0.126	0.261	0.23039	H0
		7	0.026	0.121	0.007	0.117	0.55866	H0
		8	-0.170	0.318	0.191	0.288	3.9879e-005	H1✓
		9	-0.011	0.461	0.559	0.326	1.1269e-006	H1✓

(1) Std = Standard-deviation.

The statistical analysis of the male and female first gait mode showed that the null hypothesis H0 can be rejected for the transverse angle of the ankle (p = 3.1057e-008) and frontal angle of the knee (p = 0.045316). The same analysis of the second gait mode showed that the null hypothesis H0 can be rejected for the frontal (p = 0.023485) and transverse angle of the ankle (p = 0.041766), the frontal angle of the knee (p = 0.10244) and transverse angle of the hip (p = 9.3479e-008). No significance differences were identified between the male and female third gait mode ($p < 0.05$). Through the statistical analysis of the fourth gait mode the null hypothesis H0 can be rejected for the sagittal angle of the knee (p = 0.018481), and frontal (p = 0.019026) and transverse (p = 0.00057108) angles of the hip. Finally, the statistical analysis of the fifth gait mode showed that the null hypothesis H0 can be rejected for the frontal (p =

0.011983) and transverse (p = 4.9105e-006) angles of the ankle, sagittal angle of the knee (p = 2.1052e-005), and frontal (p = 3.9879e-005) and transverse (p = 1.1269e-006) angles of the hip.

4. Conclusions

The comparative analysis among Brazilian subjects was presented. The main kinematics differences between male and female walking patterns are dependent on the hip joint. The flexion posture and the greater frontal balance are natural characteristics of the female group and influence the frontal movement of the ankle. The major flexion of the male knee is another difference in relation to the female group. The frontal orientation of the male and female knee is in agreement with their anatomical structure and no significant movements were measured in this plane, as expected.

The gait modes approach was applied with success to identify the main differences between male and female in a global sense. The advantage of the gait modes approach is the possibility of decomposing the final dynamics in a special group of functions that can indicate the contributions of all factors for the final pattern.

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7. Responsibility notice

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