DYNAMIC MODEL OF THE NORMAL HUMAN LOCOMOTION

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Abstract: *The aim of this work is to model the human locomotion system and establish a dynamic pattern of the ankle, knee and hip movement in normal locomotion. In this approach some assumptions have been made in order to simplify the model, such as: all joints was modelled as spherical and the linear movements between femur and tibia have been neglected and the angular displacements between tibia and the foot have been treated as ankle's movements. The system VICON 140 was used for motion data acquisition, which produces an infrared strobe to detect the position of skin markers and define the segments of the foot, shank, thigh and pelvis. This arrangement composes systems of orthogonal coordinates, which defines the rotation of the mechanical axis of the joints. The ground reaction forces were measured by two platforms of force. The frequency of these equipments was set in 60 Hz. The results presented in this work were obtained through the analysis of 28 young adults and are in accordance with the patterns found in the literature.*

Keywords: *human locomotion, gait analysis, dynamics*

1. Introduction

The movement always intrigued the man. Since the old Greece that the man tries to understand how this phenomenon of the nature occurs. Along the years and the humanity's scientific-industrial progress, the analysis of the movement has being transformed in a quantitative study. Etienne Jules Marey pioneering work (1834-1904), in the area of the cinematography, influenced directly the development of the biomechanics. Marey was also the first to synchronize the movement (kinematics) with measures of force (Nigg e Herzog, 1999, Andriacchi et al., 2000).

The biped form of walking is one of the most complexes of the nature. It demands, besides an appropriate physical structure, a system of extremely select control. The man needs of approximately 13 months to begin to walk. Only in the adolescence, the maturation is reached and soon lost with the aging.

The two ways to apply the equations of motion to the segments model are usually referred to as the direct and the inverse dynamics method. In the direct dynamics method, the movements of the segments are calculated by integrating the equations of motion. This is only possible when the joint moments of force are known or assumed to be zero, as a ballistic walking. In the inverse dynamics method, the joint forces and joint moments of force are calculated from a prescribed movement. Since the segmental moments, in contrast to the internal forces, can be measurement, this method is commonly applied for the analysis of measured movements. The ground reaction forces are used as an input for the dynamic approach (Sutherland et al., 1994).

In this work, a dynamical approach is presented for the calculation of the gait variables as joint angular displacements and loads. For that, a mechanical model was set up starting from the anatomical and functional structure of the lower limbs. Each articulation was modeled as a spherical joint to allow the measurement pathological movements. In this text the adopted model, the employed measurement system, the mathematical formulation and the dynamic results are presented.

2. Methods

The modeled locomotor system is composed of seven segments and six joints, presented in the Fig. (1). In the foot there are many joints that will not be considered in this work because of the impossibility, using the VICON 140 system, to observe the motion of these segments. The model considered all segment as rigid bodies.

Spherical joints models are used to estimate the movement and the forces involved in the sagittal, frontal and transverse planes. With this simplification all the translation in the joints were neglected and a uniquely rotation centre were considered. The number of degrees of freedom of this model is equal to 12 in the support phase (closed chain) and 18 in the swing phase (opened chain). During the support phase two feet are in contact with the ground while in the swing phase only one foot is in contact with the ground.

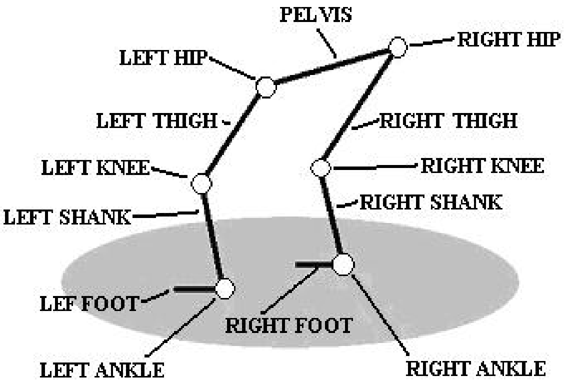


Figure 1. Mechanical model of human locomotor's system.

2.1. Experimental Protocol

Two protocols are used in this work: static and dynamic ones. While the static protocol is used to define the external local frames and the relative position of some points that are removed during the walking recording, the markers in the dynamic protocol are similar to the static without the removed points. We estimated the hip center of rotation through regression equations (Bell et al., 1989, 1990; Seidel et al., 1995; Leardini et al., 1999). Some authors used a cluster design criteria for optimization and dynamics estimation (Cappozzo et al., 1997; Andriacchi et al., 1998; Leardini et al., 1999) but this method can't be employed in the most abnormal gaits, such: cerebral palsy, total hip arthroplasty and others patients that can't do movements with great width.

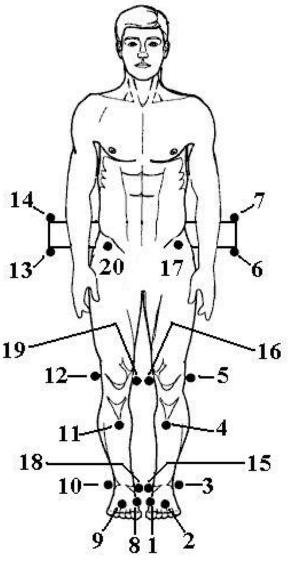


Figure 2. Experimental protocol.

The Figure (2) presents the anatomical points used in these protocols, where: (1) is the medial face of the hálux in the left foot, (2) is a point on the long axis of left foot, (3) is the lateral malleolus of left ankle, (4) is a point in the anterior surface of left shank, (5) is the lateral epicondyle of the left knee, (6) and (7) are the left vertexes of pelvis' reference structure, (8) is the medial area of is the medial face of the hálux in the right foot, (9) is a point on the long axis of right foot, (10) is the lateral malleolus of right ankle, (11) is a point on the anterior surface of right shank, (12) is the lateral epicondyle of the right knee, (13) and (14) are the right vertexes of pelvis' reference structure, (15) is the medial malleolus of left ankle, (16) is the medial epicondyle of left knee, (17) is the left anterior-superior iliac spine, (18) is the medial malleolus of right ankle, (19) is the medial epicondyle of right knee, and (20) is the right anterior-superior iliac spine.

2.2. Kinematics Theory

The body segments are modeled as rigid bodies and the relative rotation is assumed to take place about a fixed point in the center of joint (Kadaba et al., 1990; Wu et al., 1995; Raptopoulos et al., 2001, 2002). The relative rotation between adjacent segments is described in a three-dimensional space for a rotation matrix. This matrix is the product of three rotations around the axis x, y and z. The final rotation matrix is defined in the Eq. (1),

$$R_{xyz} = \begin{bmatrix} \cos\phi_y \cos\phi_z & -\cos\phi_y sen\phi_z & sen\phi_z \\ \cos\phi_x sen\phi_z + sen\phi_x sen\phi_y \cos\phi_z & \cos\phi_x \cos\phi_z - sen\phi_x sen\phi_y sen\phi_z & -sen\phi_x \cos\phi_z \\ sen\phi_x sen\phi_z - \cos\phi_x sen\phi_y \cos\phi_z & sen\phi_x \cos\phi_z + \cos\phi_x sen\phi_y sen\phi_z & \cos\phi_x \cos\phi_z \end{bmatrix} \tag{1}$$

where: ϕ_x is the rotation angle around x axis, ϕ_y around y axis, and ϕ_z around z axis.

Based on this matrix we can calculated two of these angles, ϕ_x and ϕ_z.

$$\phi_x = arctg\left({-R_{xyz}(2,3)} \big/ {R_{xyz}(3,3)} \right) \tag{2}$$

$$\phi_z = arctg\left({-R_{xyz}(1,2)} \big/ {R_{xyz}(1,1)} \right) \tag{3}$$

To calculate the angle ϕ_y it is necessary to manipulate the Eq. (1). Pos-multiplication the matrix in Eq. (1) for the inverse of the rotation matrix around z axis we can construct a new matrix that is the product of the rotation around x and y axis (Eq. 4).

$$R_{xy} = R_{xyz}.(R_z)^{-1} = \begin{bmatrix} \cos\phi_y & 0 & sen\phi_y \\ sen\phi_x sen\phi_y & \cos\phi_x & -sen\phi_x \cos\phi_y \\ -\cos\phi_x sen\phi_y & sen\phi_x & \cos\phi_x \cos\phi_y \end{bmatrix} \tag{4}$$

So, the angle ϕ_y will be calculated by Eq. (5).

$$\phi_y = arctg\left({R_{xy}(1,3)} \big/ {R_{xy}(1,1)} \right) \tag{5}$$

2.2.1. Inertial and Local Frames

The inertial coordinate system is defined, in the laboratory, as presented in Fig. (3). In this figure can be seen the segments, the walking way and the inertial frame.

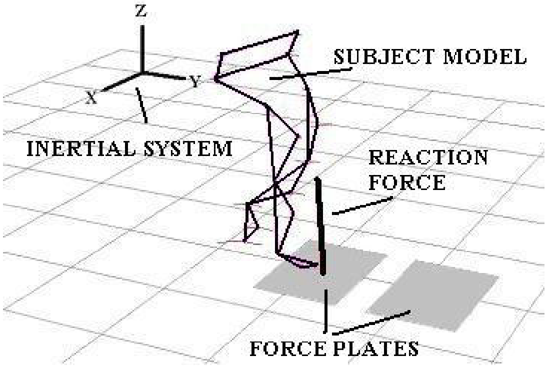


Figure 3. Inertial coordinate system.

In this work, two types of local frames are considered, the external and internal. The external reference system is used to define the position of the removed marks at the transformation from the static for the dynamic protocol. The internal reference system is used to calculate the joint relative angles and the net forces and moments in each articulation. For each joint there are two adjacent local frames to calculate the rotation around each axis making up six local frames near each joint. The exception is in the hip, where there are three references in the femur and only one in the pelvis. The Figure (4) presents the external and internal frames of one leg,

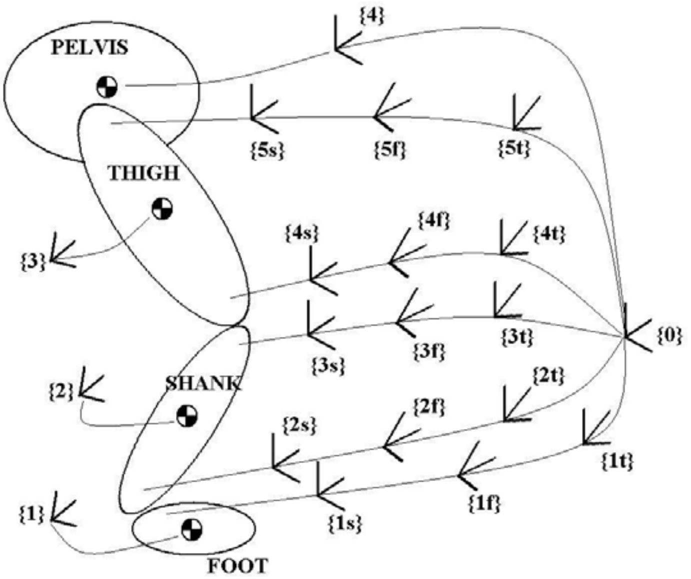


Figure 4. External and internal frames of one leg.

where: {0} is the inertial reference system, {k} is the center of mass system of the segment k (k=1..4), {ps} is the local frame used to calculated the sagittal rotation of the joint (p=1..5), {pf} is the local frame used to calculated the frontal rotation of the joint (p=1..5) and {pt} is the local frame used to calculated the transverse rotation of the joint (p=1..5). These systems are used to represent the different rotation axis in this approach.

2.3. Kinetics Theory

The Figure (5) shows the free-body diagram of body i, where: ${}^{i}F_{i-1,i}$ is the force acting from the body i-1 in the body i and described in the center of mass reference system, ${}^{i}M_{i-1,i}$ is the moment of force acting from the body i-1 in the body i, ${}^{i}F_{i+1,i}$ the force from the body i+1 in the body i, ${}^{i}M_{i+1,i}$ is the moment of force from the body i-1 in the body i, ${}^{i}r_{i-1}^{i}$ is the position of joint i-1 relative to the centre of mass of segment i, ${}^{i}r_{i}^{i}$ is the position of joint i relative to the centre of mass of segment i , ${}^{i}a_{i}$ is the acceleration of the centre of mass of segment i, ${}^{i}w_{i}$ is the angular velocity of segment i, ${}^{i}\dot{w}_{i}$ is the angular acceleration of segment i and m_{i} is the mass of segment i. All these variables are described in the local reference system of centre of mass {i}.

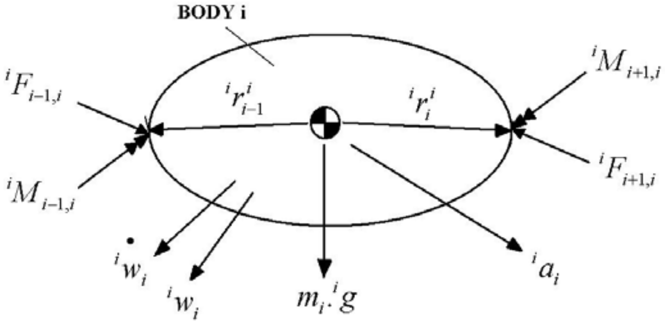


Figure 5. General diagram of loads for each body.

Adding all forces that act on the body and equaling them to the net force, is defined the Eq. (6), which calculates the force by the body i+1 on the body i. This equation describes de force in the center of mass reference system.

$$ {}^{i}F_{i+1,i} = m_{i}.\left({}^{i}a_{i} - {}^{i}g\right) - {}^{i}F_{i-1,i} \tag{6} $$

Adding all moments that act on the body and equaling them to the net moment of force, is defined the Eq. (7), which calculates the moment of force exercised by the body i+1 on the body i. This equation describes de moments around the center of mass reference system.

$$ {}^{i}M_{i+1,i} = {}^{i}I_{i} \cdot {}^{i}\dot{w}_{i} + {}^{i}w_{i} \times {}^{i}I_{i} \cdot {}^{i}w_{i} - \left({}^{i}r^{i}_{i-1} \times {}^{i}F_{i-1,j} \right) - {}^{i}M_{i-1,i} - \left({}^{i}r^{i}_{i+1} \times {}^{i}F_{i+1,j} \right) \qquad (7) $$

The anthropometrical parameters (mass, inertia, etc.) were estimated through regression equations obtained from the gamma scanner method (Zatsiorsky et al., 1990). Knowing the transformation matrixes between the references is easy to transform these loads from the center of mass system for another system and it will be used to present the results.

2.4. Materials and Equipments

The motion analysis was performed using a computer-aided video motion analysis system with three infrared cameras (VICON140) and two platforms of force (Bertec Co.). The walking way and the equipments of the gait lab are presented in the Fig. (6).

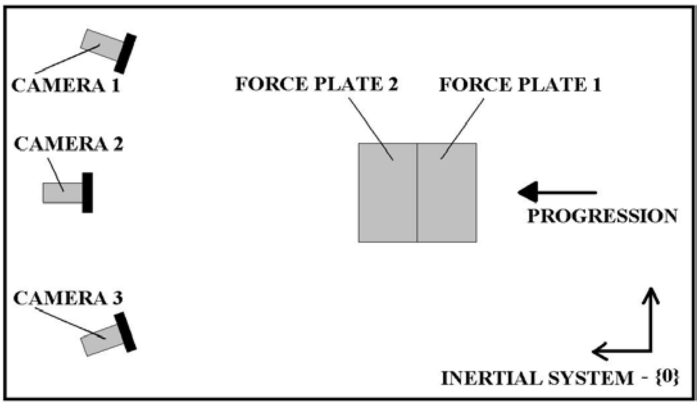


Figure 6. Walking way and equipments of the gait lab.

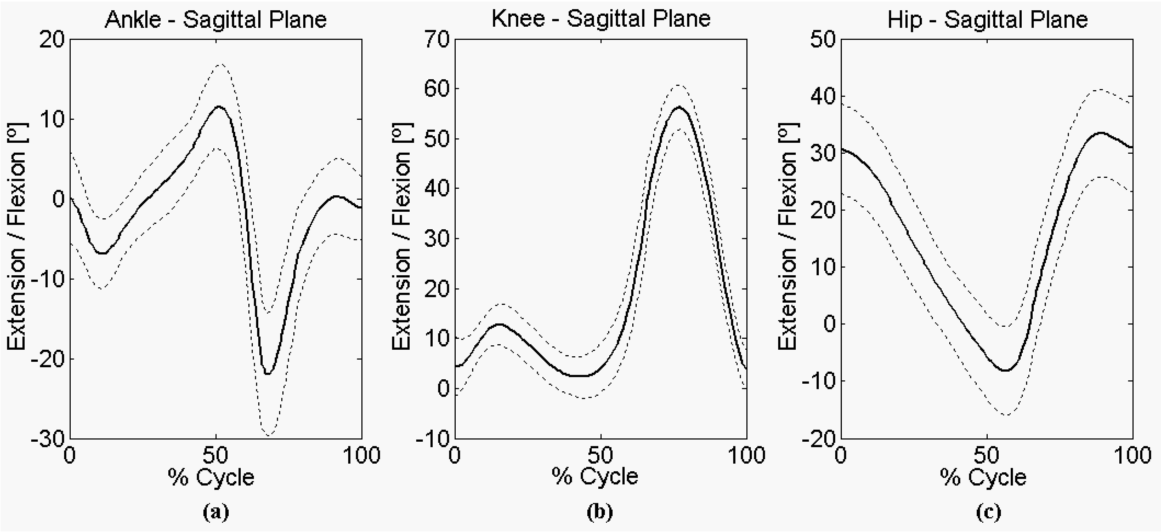
A group of 28 normal healthy subjects without history of musculoskeletal problems was analyzed. This group was formed by 11 men and 17 women and their characteristics are described in the Tab (1).

Table 1. Characteristics of the group of control.

Characteristic	Unit	Medium	Standard deviation
Age	[years]	22.27	2.16
Mass	[kg]	66.500	14.888
Height	[m]	1.689	0.091
Cycle	[s]	1.241	0.127
Support phase	[s] / [% cycle]	0.824 / 66.37	0.092 / 2.48
Swing phase	[s] / [%cycle]	0.417 / 33.63	0.051 / 2.48
Stride	[m]	1.165	0.092
Step	[m] / [% stride]	0.584 / 50.10	0.061 / 4.55
Width of the base	[m]	0.123	0.034
Progression speed	[m/s]	0.949	0.116
Cadence	[steps/min]	98.021	9.508

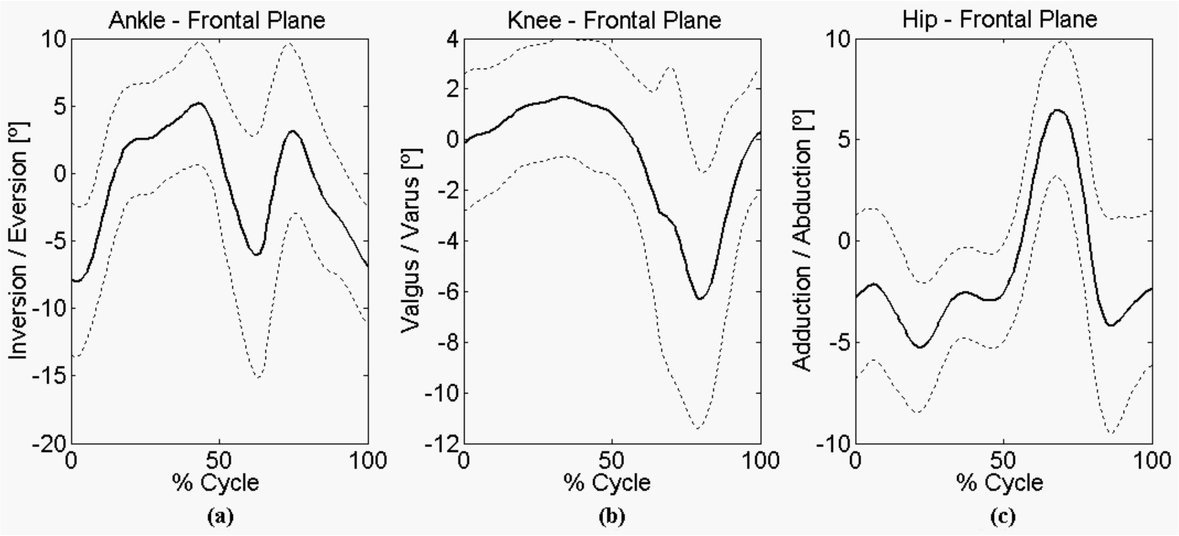
3. RESULTS

The Figures (7) to (15) show the mean and standard deviation of the angular displacements, forces and moments acting in the ankle, knee and hip joints. There were no significant differences between men and women subjects. Zero percent of cycle corresponds to the heel strike and 100% corresponded to the next hell strike of the same limb.



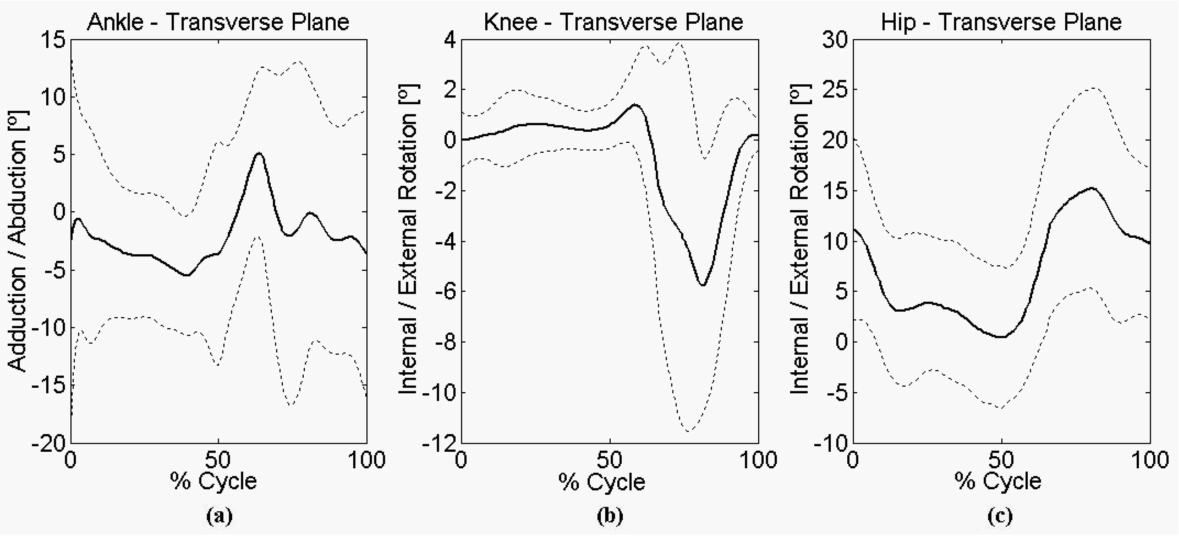
(a) (b) (c)

Figure 7. Sagittal angles of joints: (a) ankle, (b) knee and (c) hip.



(a) (b) (c)

Figure 8. Frontal angles of joints: (a) ankle, (b) knee and (c) hip.



(a) (b) (c)

Figure 9. Transverse angles of joints: (a) ankle, (b) knee and (c) hip.

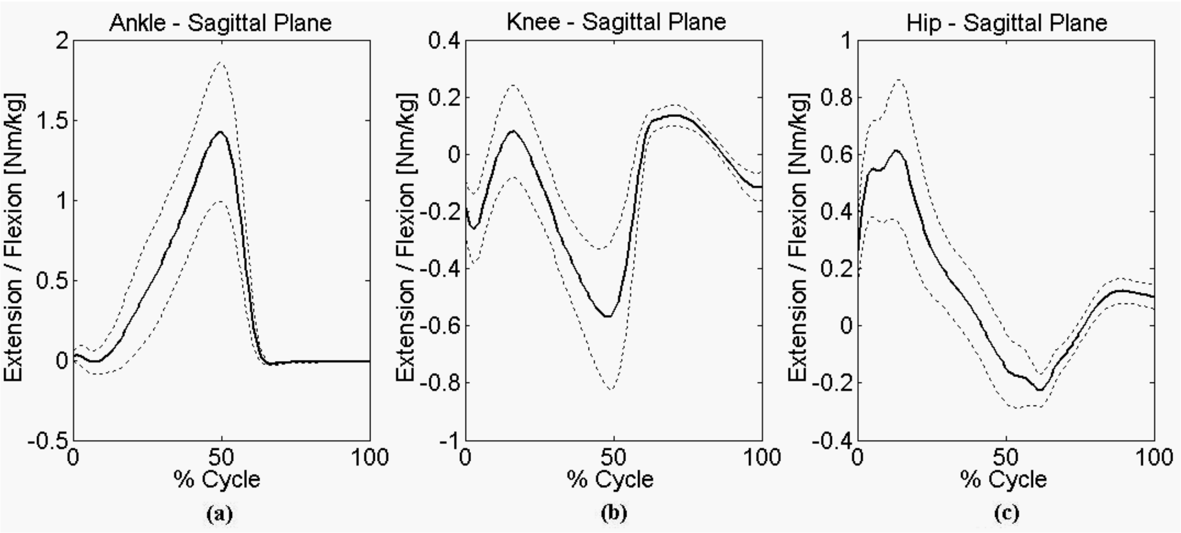


Figure 10. Sagittal moments of force: (a) ankle, (b) knee and (c) hip.

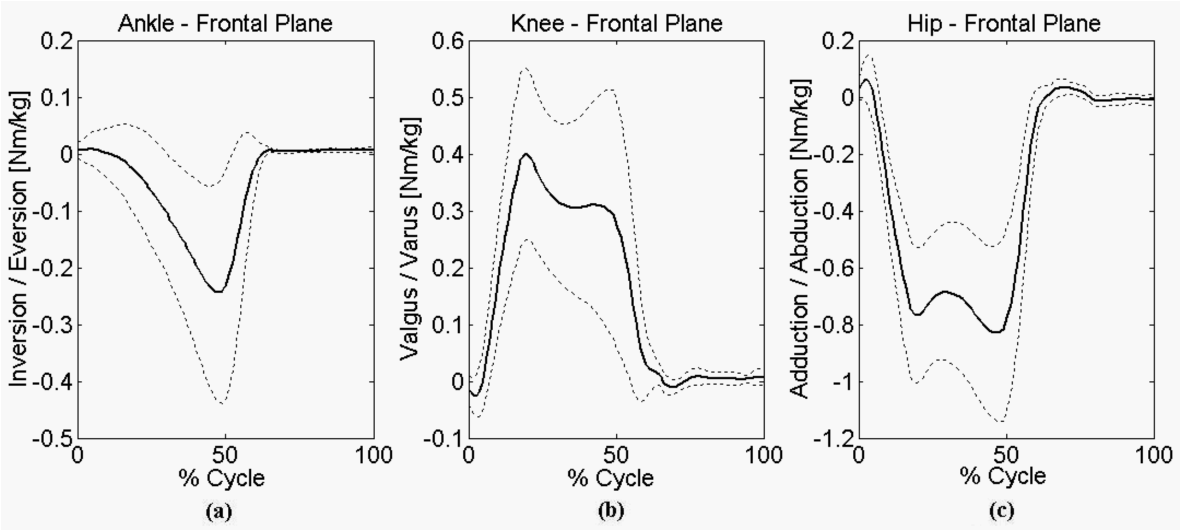


Figure 11. Frontal moments of force: (a) ankle, (b) knee and (c) hip.

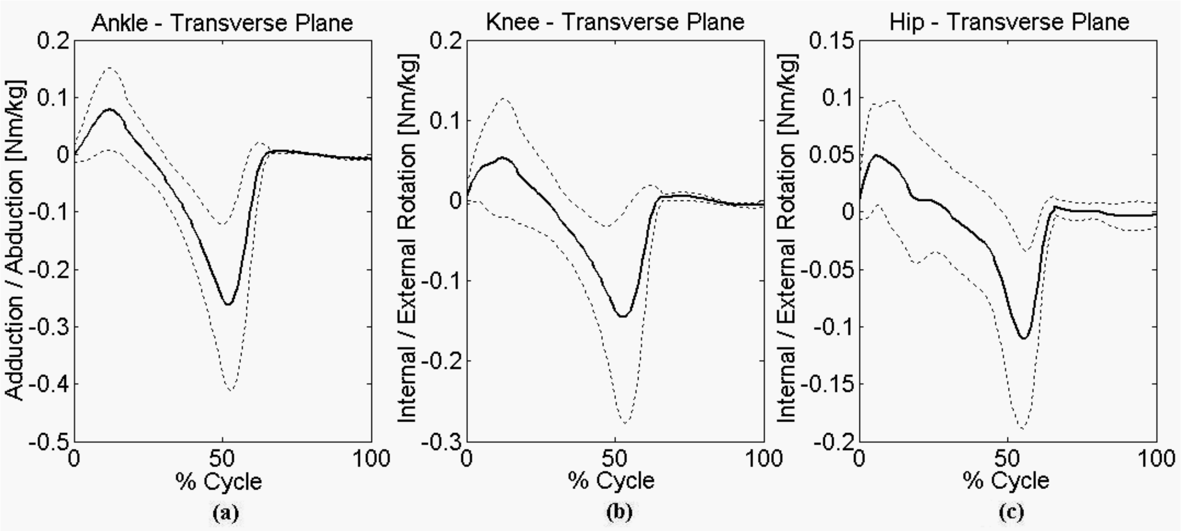


Figure 12. Transverse moments of force: (a) ankle, (b) knee and (c) hip.

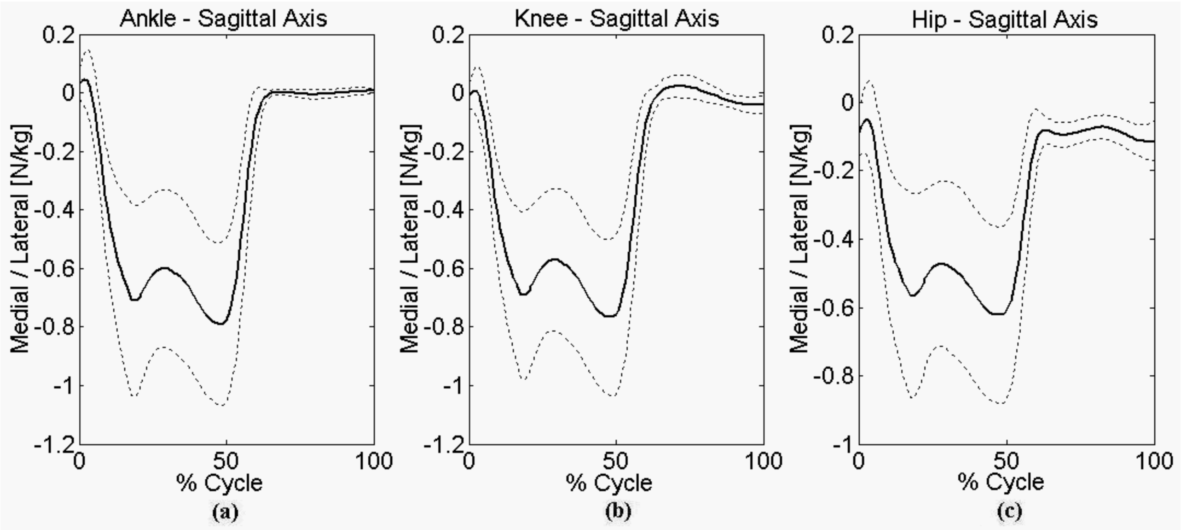


Figure 13. Medial and lateral forces on: (a) ankle, (b) knee and (c) hip.

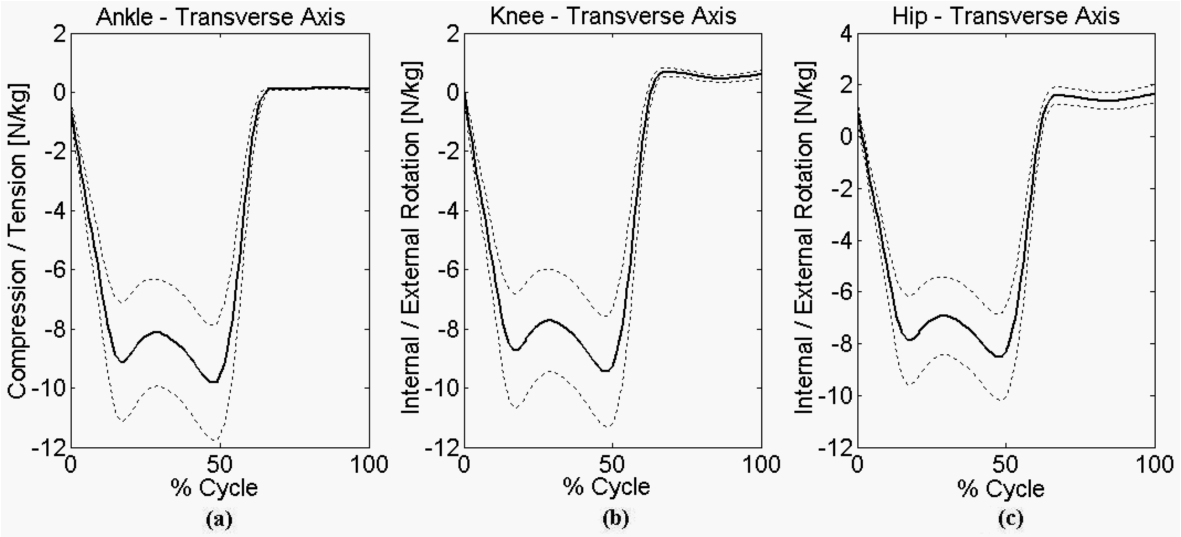


Figure 14. Posterior and anterior forces on: (a) ankle, (b) knee and (c) hip.

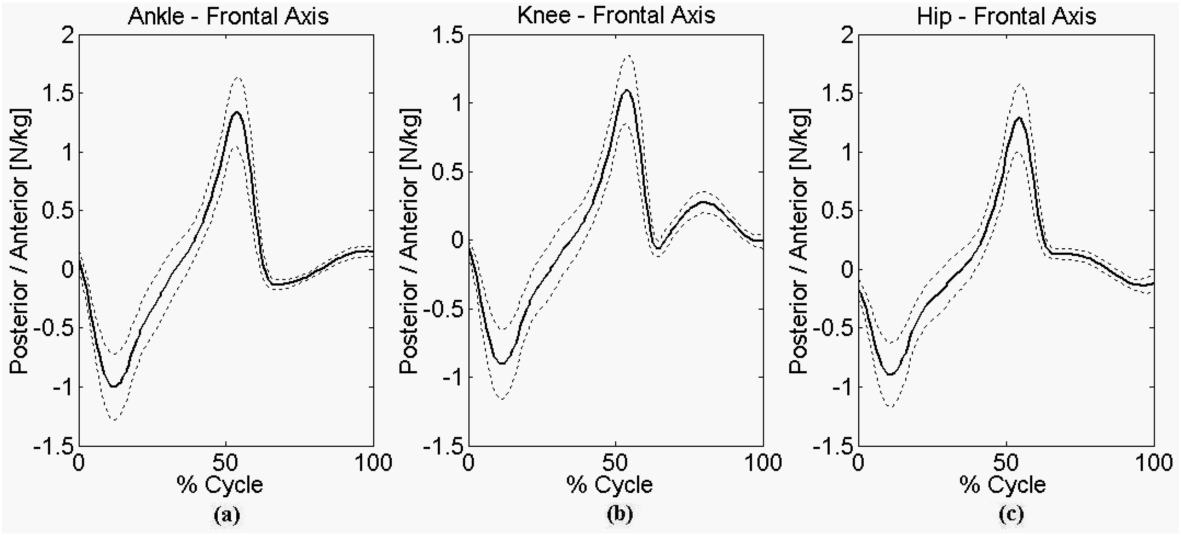


Figure 15. Compression and tension forces on: (a) ankle, (b) knee and (c) hip.

4. Discussion and Conclusion

In this paper, we have presented a detailed description and implementation of a method to calculate the dynamical variables of human walking using a three-dimensional approach and a rigid body model. The local reference frames were constructed to represent the anatomical and mechanical axis.

The kinematics shows that the sagittal plane has the best results and minimum standard deviation while the variability in the frontal and transverse planes are greater. The Table (2) presents a comparison between the results of this work and some literature values.

Table 2. Comparison of the mean angular displacements (adapted from Kadaba et al., 1990).

	This work	Kadaba (1990)	Sutherland (1980)	Winter (1983)	Chao (1983)	Murray (1964)
Nº of subjects	28	40	15	16	110	60
HIP						
Sagittal	41.7	43.2	43.0	43.0	X	42.0
Frontal	11.7	11.6	14.0	X	X	X
Transverse	14.8	13.0	9.0	X	X	X
KNEE						
Sagittal	54.1	56.7	58.0	64	69.0	60.0
Frontal	8.0	13.4	X	X	10.0	X
Transverse	7.1	16.0	9.0	X	13.0	X
ANKLE						
Sagittal	33.5	25.5	28.0	28.0	X	28.0
Frontal	13.2	X	X	X	X	X
Transverse	10.6	15.7	17.0	X	X	X

The kinetic shows the same shape and values that have been published in the literature (Winter, 1991; Sutherland, 1994). The results of the kinetics show a great variability in the frontal moments, these could be a consequence of the lateral balance - characteristic of woman locomotion.

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