CALCULATION OF THE CARDAN ANGLES AT THE HIP JOINT USING THE ISB-RECOMMENDATION TO DEFINE THE JOINT COORDINATE SYSTEM

Claysson Vimieiro
Laboratório de Bioengenharia - Labbio
Departamento de Engenharia Mecânica
Universidade Federal de Minas Gerais – UFMG
Av. Antônio Carlos, 6627 – 31.270-901 – Belo Horizonte, MG - Brasil
claysson@demec.ufmg.br

Emanuel Andrada
Fachgebiet Biomechatronik
Fakultät für Maschinenbau
Technische Universität Ilmenau
Ehrenbergstrasse 29 – 98693 – Ilmenau – Thüringen - Deutschland
Emanuel.Andrada@tu-ilmenau.de

Susanne Lipfert
Locomotion Laboratory - Lauflabor
Institut für Sportwissenschaft
Friedrich-Schiller-Universität Jena
Dornburger Straße 23 – 07743 – Jena – Thüringen - Deutschland
s.lipf@uni-jena.de

Hartmut Witte
Fachgebiet Biomechatronik
Fakultät für Maschinenbau
Technische Universität Ilmenau
Ehrenbergstrasse 29 – 98693 – Ilmenau – Thüringen - Deutschland
Hartmut.Witte@tu-ilmenau.de

Marcos Pinotti
Laboratório de Bioengenharia - Labbio
Departamento de Engenharia Mecânica
Universidade Federal de Minas Gerais – UFMG
Av. Antônio Carlos, 6627 – 31.270-901 – Belo Horizonte, MG - Brasil
pinotti@ufmg.br

Abstract. *The main purpose of the present study was calculate the cardan angles at the hip joint comparing two methods to estimate the Hip Joint Center (HJC). The skin marker positions and the Joint Coordinate System (JCS) were defined using the International Society of Biomechanics (ISB) recommendation. This JCS definition requires the estimate of the HJC location that was performed using both predictive and functional methods. In order to track the motion of the hip and lower limbs, 6 healthy test-persons with no previous history of musculoskeletal injury walked without shoes on a treadmill in upward and downward profiles at velocities from 2,0 to 4,0 km/h with velocity steps of 0,5km/h. The gait motions were taken using 8 Qualisys® infrared cameras at a sampling frequency of 240 Hz. In addition, Ground Reaction Forces (GRF) were colected to define the stride cycle to analyse the Qualisys data. An especial hip motion type (Star-Arc) was performed to estimate the HJC for the functional method. The cardan angles at the hip joint were computed using a sequence of rotations that cause the first rotation corresponding to flexion–extension, the second to internal–external rotation, and the third to abduction–adduction. A Matlab® routine was developed to compute the gait analysis data. During the data acquisition, the knee markers location generated a visualization problem in the Qualisys motion system. The cameras had to be disposed in a specific set position, reducing the repeatability of the acquisition. The cardan angles results suggested that Bell's method (predictive method) exhibit a close result to the functional method in the x and z-directions.*

Keywords: *Gait analysis, Cardan Angle, Hip Joint Center, Joint Coordinate System, ISB Recommendation.*

1. INTRODUCTION

One important modelling approach for the human neuromechanical structure is the gait analysis. It can help in the orthopedical and neurological rehabilitation process. Motion analysis of the lower extremities usually requires determination of the location of the Hip Joint Center (HJC). In human analysis the HJC is used to define the anatomical frame of the femur and as the reduction point of the external loads when estimating the hip muscular moment (Cappozzo et al., 1995; Wu et al, 2002).

The location of the HJC can be estimated using either a predictive method (Bell et al., 1990; Davis et al.,1991) or a functional methods (Leardini et al., 1999). The predictive method uses regression equations that provide an estimate of the coordinates of the HJC in a pelvic anatomical frame as a function of anthropometric quantities. The functional method identifies the HJC as the relevant center of rotation, using the relative motion of the thigh and pelvis.

Leardini et al. (1999) evaluated the accuracy of the functional method for hip joint center determination by comparing its results to those obtained using radiographs to locate the center of the femoral head. In this study just healthy subjects were evaluated and subjects with limited range of motion at the hip were not considered. Camomilla et al. (2006) reported that the functional method can be successfully implemented when range of motion is limited but still requires collection of a special motion trial in which hip motion in both sagittal and frontal planes are recorded.

In order to get the kinematical paths of the gait for a test-person, the motion of limbs and body segments can be captured by the Qualisys® Pro-Reflex® System, using passive markers attached on bony marks. This kinematical data allows the calculation of the cardan angles that can provide a representation of joint orientation and an alternative method of describing the orientation of rigid body segments in space (Herzog et al., 2002). They are a set of three angles which represent sequential rotations of a segment about each of its three body-fixed axes. To calculate the cardan angle, the coordinate system for the segments must be defined.

As there are many approaches to define the coordinate system for human motion, the International Society of Biomechanics (ISB) recommends a definition of the Joint Coordinate System (JCS) for human joint motion (Wu et al, 2002). The main reason of these recommendations is to make possible the comparison among various studies, but there are not many published studies using the ISB recommendations for lower extremities.

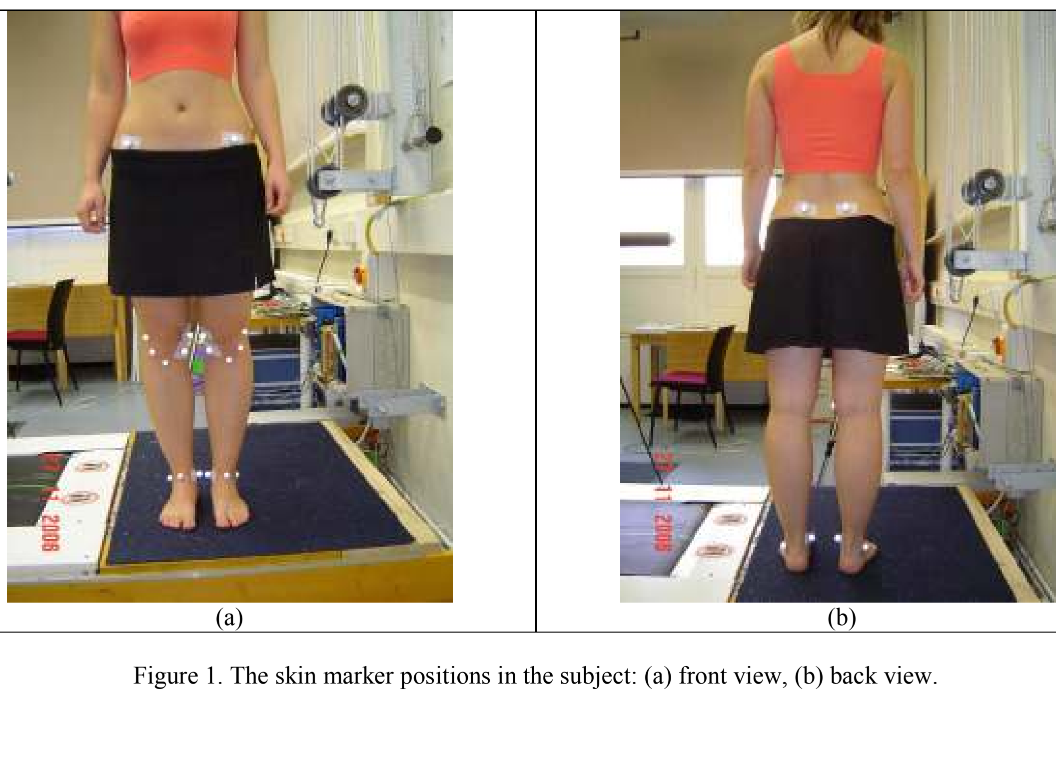
The purpose of the present study was to calculate the cardan angles at the hip joint using the ISB recommendation to establish the pelvic and femoral coordinate system and the anatomical landmarks for the skin marker positions. To estimatate the HJC was used both the predictive and functional methods.

2. MATERIALS AND METHODS

Six test-persons (three males and three females) with pain free and no previous history of musculoskeletal injury or disease have participated in this study. The subjects signed an informed consent form prior to testing.

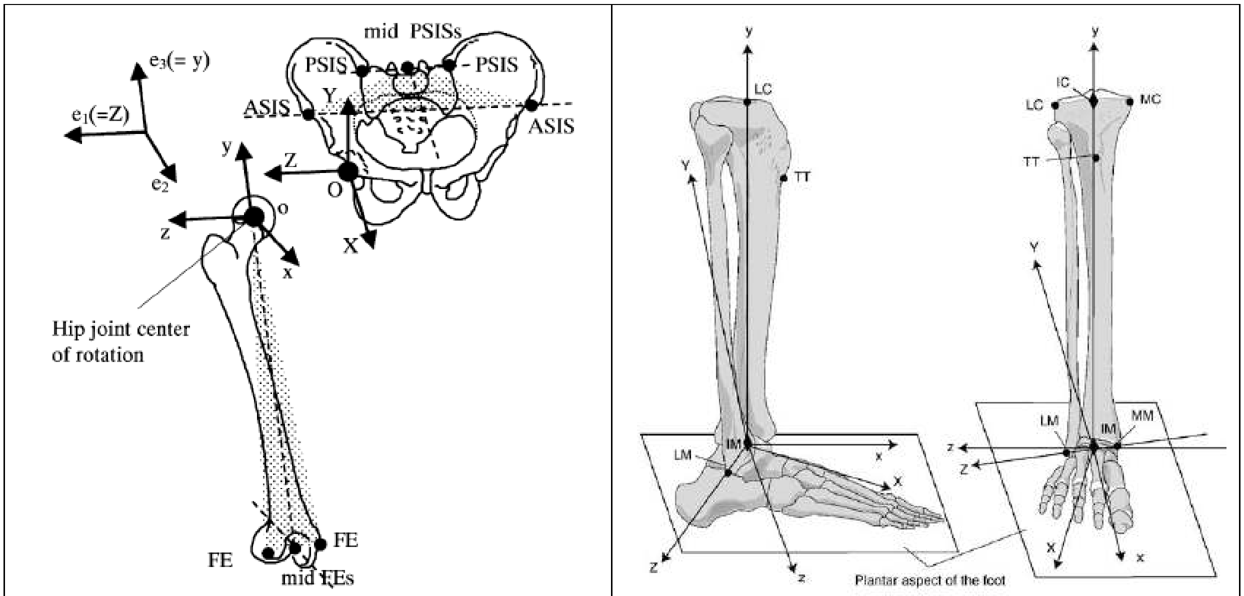
In order to track the motion of the hip and lower limbs, the subjects walked without shoes on a treadmill in upward and downward profiles at velocities from 2,0 to 4,0 km/h with velocity steps of 0,5km/h. The gait motions at each velocity were taken in periods of 15 seconds with 8 Qualisys® infrared cameras at a sampling frequency of 240 Hz.

The skin marker positions (Fig. 1) and the JCS (Fig. 2) were determined using the ISB recommendation (Wu et al, 2002). They are defined based on bony landmarks that are either palpable or identifiable from X-rays. In addiction, Ground Reaction Forces (GRF) were colected to define the stride cycle to analyse the Qualisys data.



(a) (b)

Figure 1. The skin marker positions in the subject: (a) front view, (b) back view.



(a) (b)

Figure 2. Joint coordinate system: (a) pelvic (XZY) and femoral (xzy), (b) Tibia/Fibula (XZY) and Calcaneus (xzy) (Wu et al, 2002).

2.1. Hip Joint Center (HJC)

The HJC was calculated using both predictive and functional methods. The prediction approach uses Regression Equations (REs) with independent anthropometric parameters describing the geometry of the pelvis. The REs proposed by Bell et al. (1990) and by Davis et al. (1991) are the most widely used.

Camomilla et al. (2006) has presented a research about algorithms used to estimate the HJC for functional methods. The authors reported that the algorithm Center of the bias-compensated quartic best fillet sphere (S4) is recommend, because this method may be less sensitive to the marker cluster deformation associated with soft tissue artefacts. In addition, the S4 method shares the lowest computation time.

Predictive Method

The anthropometric parameters used in prediction approach are the pelvic width (PW), the antero/posterior component of the distance between a point approximating the hip centre and the homolateral ASIS (D) and the distance between ASIS and homolateral medial malleolus (L). The REs proposed by Bell are:

$$\begin{aligned} x &= -0.19PW; \\ y &= -0.30PW; \\ z &= 0.36PW; \end{aligned} \tag{1}$$

and by Davis are:

$$\begin{aligned} x &= -0.95D + 0.031L - 4; \\ y &= -0.31D - 0.096L + 13; \\ z &= 0.5PW - 0.055L + 7; \end{aligned} \tag{2}$$

where x, y, and z are the local coordinates of the right HJC in the pelvic anatomical coordinete system.

Functional Method

For the estimation of the center of rotation using the functional approach, the algorithm Center of the bias-compensated quartic best fillet sphere (S4) was used. In S4 method, the center of rotation was determined through a closed form minimization of the quartic function (Gamage and Lasenby, 2002):

$$f\left(m, r^{p}\right)=\sum_{p=1}^{M}\sum_{k=1}^{N}\left[\left(v_{k}^{p}-m\right)^{2}-\left(r^{p}\right)^{2}\right]^{2} \tag{3}$$

where r^{p} is the radius of the sphere defined by the k[th] marker, m is the center of rotation and v_{k}^{p} denote the position of marker p at time k. M is the number of markers and N is the number of frames.

To overcome the bias problem, Halvorsen (2003) proposed a modified approach, named the bias compensated algebraic sphere fit method, where the bias is interactively reduced.

The bias that affects the solution of Eq. 3 is compensated by solving it interactively, using in each interaction the previous solution as initial estimate and introducing a correction term, which incorporates the latter estimate and a model of the photogrammetric error (Halvorsen, 2003). The calculation of the center of rotation involves solving the linear system of equations.

$$Am = b \tag{4}$$

where

$$A = 2\sum_{p=1}^{M}\left\{\left(\frac{1}{N}\sum_{k=1}^{N}v_{k}^{p}\left(v_{k}^{p}\right)^{T}\right)-\overline{v^{p}}\,\overline{\left(v^{p}\right)}^{T}\right\} \tag{5}$$

$$b = \sum_{p=1}^{M}\left[\left(\overline{\left(v^{p}\right)^{3}}-\overline{v^{p}}\,\overline{\left(v^{p}\right)^{2}}\right)\right] \tag{6}$$

and the averages are defined by:

$$\overline{v^{p}} = \frac{1}{N}\sum_{k}v_{k}^{p} \tag{7}$$

$$\overline{\left(v^{p}\right)^{2}} = \frac{1}{N}\sum_{k}\left(v_{k}^{p}\right)^{T}v_{k}^{p} \tag{8}$$

$$\overline{\left(v^{p}\right)^{3}} = \frac{1}{N}\sum_{k}v_{k}^{p}\left(v_{k}^{p}\right)^{T}v_{k}^{p} \tag{9}$$

Hip Motion Type

In accordance with Heller et al. (2006), the performance of all approaches decreased approximately exponentially with decreasing the hip range of motion. Camomilla et al. (2006), suggested to use the *Star-Arc* hip movement because it is yield the better performance to calculate the HJC, irrespective of the method used. When using the functional method, varying the direction of movement is more important to accurate HJC location than performing motions that are large in magnitude.

The *Arc* movement is a Flexion of 30º, half circumduction to extension of 30º and back to neutral position. The *Star* movement are seven flexion-extension/abduction-adduction combined movements from the neutral position within the perimeter drawn in the *Arc* movement. The *Star-Arc* movement is a *Star* movement followed by *Arc* movement. We have consequently asked the subject to perform continuously and sequentially a *Star-Arc* movement.

2.2. Cardan Angles

The Cardan angles are obtained as an ordered sequence of three basic rotations that occur about three separate axes (Vaughan, 1997). The parametric rotation matrices for rotations about the x, y and z axes of a Cartesian coordinate system are defined by R_i, R_j and R_k. Since matrix multiplication is not commutative, the final parametric rotation matrix (R_{ijk}) depends on which of the axes x, y or z is chosen for the rotations i, j and k. Therefore, the parameterization of the rotation matrix into Cardan angles is sequence dependent (Herzog et al., 2002). The sequence of the successive rotations can vary depending on the intention of the analysis.

The cardan angles at the hip joint were computed using decomposition of the transformations between the femoral and pelvic anatomical coordinate systems, which were computed for each frame of motion data. A ZXY sequence of rotations was chosen, causing the first rotation corresponding to hip flexion–extension, the second to internal–external rotation, and the third to abduction–adduction.

The first rotation (γ) is about the Z axis of the pelvic JCS. The second rotation (α) is about the X axis of the femoral JCS, in the orientation it assumes after the first rotation is performed and the third rotation (β) is about the Y axis of the femoral JCS in the new orientation after the first and second rotations. The orientation matrix (Eq. 10) is given by:

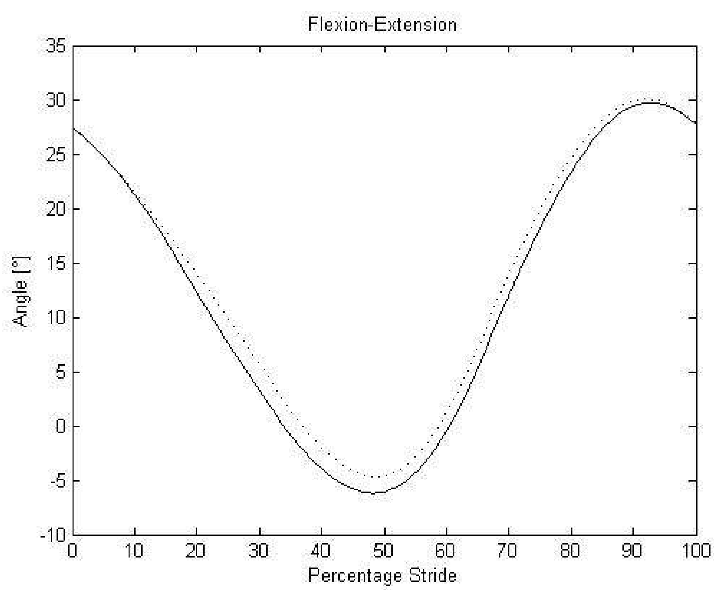
$$R_\gamma R_\alpha R_\beta = \begin{bmatrix} \cos\gamma\cos\beta - \sin\gamma\sin\alpha\sin\beta & -\sin\gamma\cos\alpha & \cos\gamma\sin\beta + \sin\gamma\sin\alpha\cos\beta \\ \sin\gamma\cos\beta + \cos\gamma\sin\alpha\sin\beta & \cos\gamma\cos\alpha & \sin\gamma\sin\beta - \cos\gamma\sin\alpha\cos\beta \\ -\cos\alpha\sin\beta & \sin\alpha & \cos\alpha\cos\beta \end{bmatrix} \quad (10)$$

2.3. Matlab Rotine

The gait analysis data were computed using a Matlab® routine. These routine is composed for 3 modules: The first module performs the interpolation and filtering of Qualisys and GRF data. The second module performs the HJC calculation for the predictive and functional methods as well as the construction of the body coordinate systems. The third module finally calculates the Cardan angles.

3. RESULTS AND DISCUSSION

To calculate the cardan angles, the pelvic and femoral JCS were defined using the HJC calculated by Bell (predictive method) and by functional method (Fig. 3). The results were:



(a)

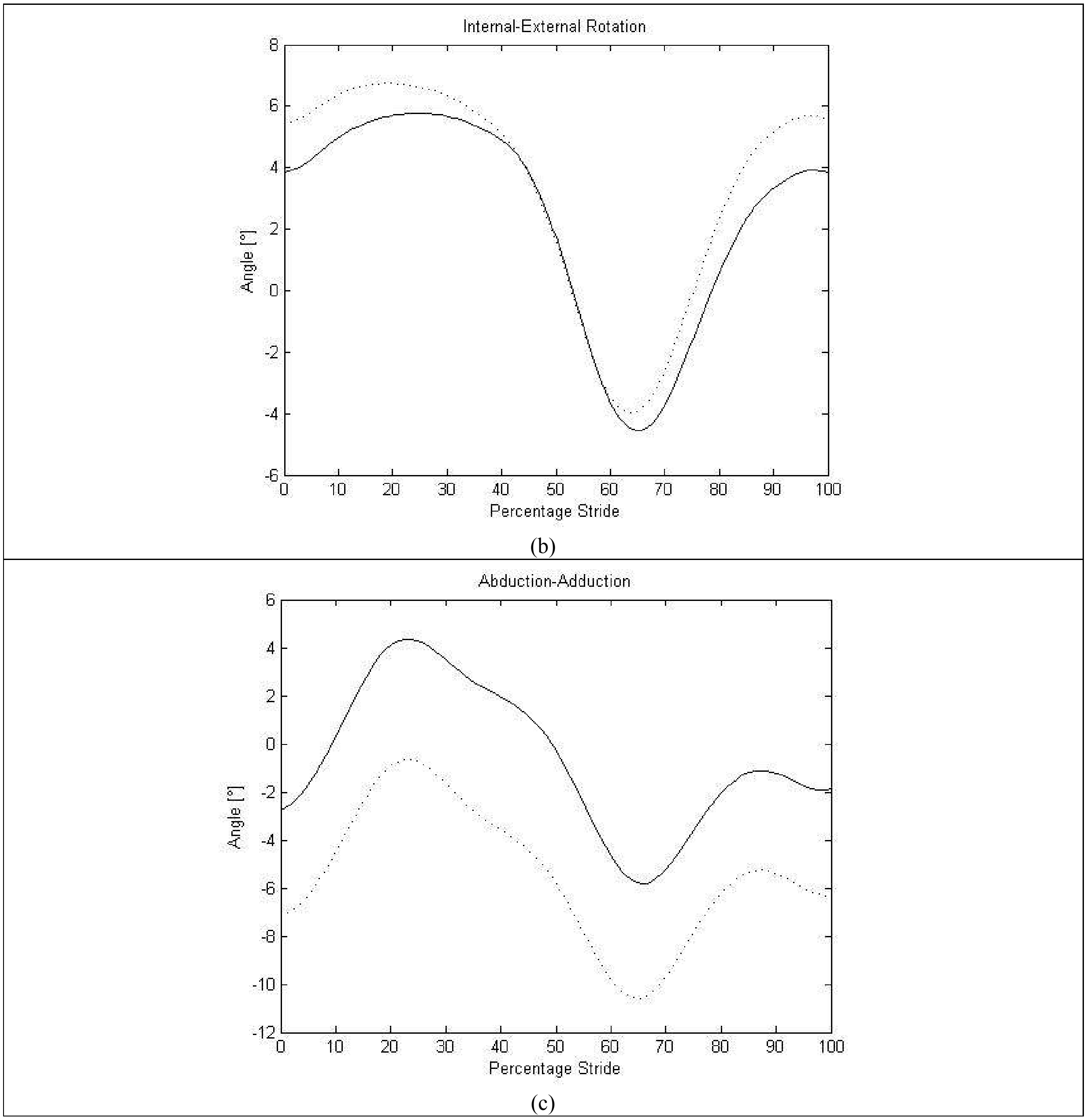


Figure 3. Cardan angles (a) Flexion–extension, (b) internal–external rotation, (c) abduction–adduction. Cardanic angles with HJC calculated by Bell are presented by the solid line. Cardanic angles with HJC calculated by functional method are presented by the dotted line.

The angles were showed in function of the percentage of the gait cycle. The gait cycle was defined starting in the heel strike of the right calcaneus and finishing in the next heel strike of the same calcaneus. Swing phase is from 60% to 100% of the gait cycle. The increase of the angles is associated with flexion, adduction and internal rotation, respectively.

During the data acquisition for the gait motion using the ISB recommendation, the knee markers located in the medial femoral epicondyle and in the medial tibial condyle pass very close in both legs. This situation generated a visualization problem in the Qualisys motion system. To obtain a reasonable visualization for all markers, it was necessary to use the 8 cameras disposed in a specific set position. Thus, the repeatability of the method was reduced. The occurrence of this problem was found higher in female.

The cardan angles results presented here are only from one subject (female) and in the sequence of this study an assessment between subjects will be performed. An especial hip motion type (Star-Arc) was performed to estimate the

HJC for the functional method. This type of motion allow an accurately locate for the HJC when using the functional method.

Leardini et al. (1999) made a comparison for the HJC coordinates obtained using the regression equations proposed by Bell et al. (1990) and reported that this method exhibit a better accuracy in the x- and z-directions comparing with the y- direction. The large offset observed in the abduction–adduction results, the y-direction (figure-3c) also suggested this behavior.

The two methods produced highly close results for flexion-extension data, moderately close results for internal-external rotation data and less close results for abduction-adduction data.

4. CONCLUSION

It was calculated the cardan angles at the hip joint for the gait movement using the ISB recommendations to define the JCS and the anatomical landmarks for the skin marker positions. The ISB recommendations require the estimation of the HJC location. This was performed using both predictive and functional methods.

Variations in the method or in the number and position of skin markers can affect the accuracy of the results. The Qualisys motion analysis data can be affected by skin movement artifacts, anatomical landmark uncertainty and the cameras calibration system.

However, it is necessary to estimate the error in joint angle calculation. This analysis will be performed in further steps of this work.

5. ACKNOWLEDGEMENTS

Authors wish to acknowledge the Locomotion Laboratory (Lauflabor) in University of Jena for the availability of the equipments for the data acquisition and the financial support of DAAD and CAPES (Proc. BEX 2111/06-3) and CNPq (Proc. 1279447203207655).

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