Report:
Method to estimate the localization of the thigh frontal plane to apply in Gait Analysis.

1. Introduction

The objective of this study were to determine an additional method to estimate the thigh frontal plane, where afterwards will be generated a local coordinates system for a measurement of the relatives movements between the thigh and its adjacent segments: pelvis and shank. The measured values of the hip rotation and valgus-varus of the knee, by a gait analysis system, suffer important changes due to the error in the frontal plane of the thigh determination, what may affect negatively the clinical decision to be followed.

The estimation of the thigh frontal plane was performed through of the determination of a control variable related to the rotations occurred on the knee joint, to a determined type of movement performed, as described in the section 2.3. The knee flexion-extension axis and, by consequence, the thigh frontal plane, derive from this control variable.

The validity of utilization of this method was verified by mean of a realization and later statistics comparison from a series of 23 exams of gait in normal subjects, where were used the value generated by the control variable and by the standard protocol of gait analysis, with the use of the Knee Alignment Device (KAD).

2. Methods

2.1 Instrumentation

The kinematics data were collected from the system of tridimensional analysis of gait Vicon 370 - version 2.5 - (Oxford Metrics Limited; UK) with 6 cameras of 60 Hz. It was used the Helen Hayes Marker Sets increased of 8 markers (figure 1), to generate four additional system of coordinates on the thighs and legs (figure 2). The data were processed subsequently with the programs Vicon Clinical Manager (VCM) - version 1.34/1.37 - and Mathcad 2000 (Mathsoft, Inc; USA).

2.2 Assumption of the Calculation Model

The determination of the control variable, used to correlate the position of the thigh frontal plane with the rotations occurred on the knee joints, was done by a calculation model with a simplified assumption on the knee movements, to be used in subjects with limited movement and posture. All the translations movements that occur on the knee were slight, and only the relative rotations between the segments of thigh and shank were used as parameter of analysis.

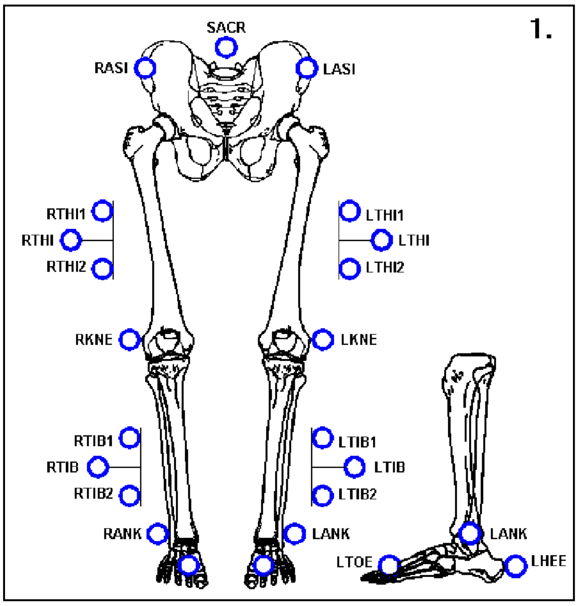


Figure 1.
Helen Hayes Marker Sets increased with 8 markers LTHI1, LTHI2, RTHI1, RTHI2, LTIB1, LTIB2, RTIB1 and RTIB2.

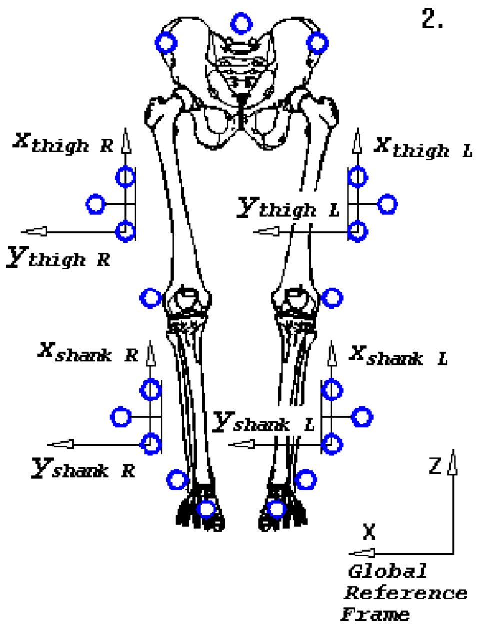
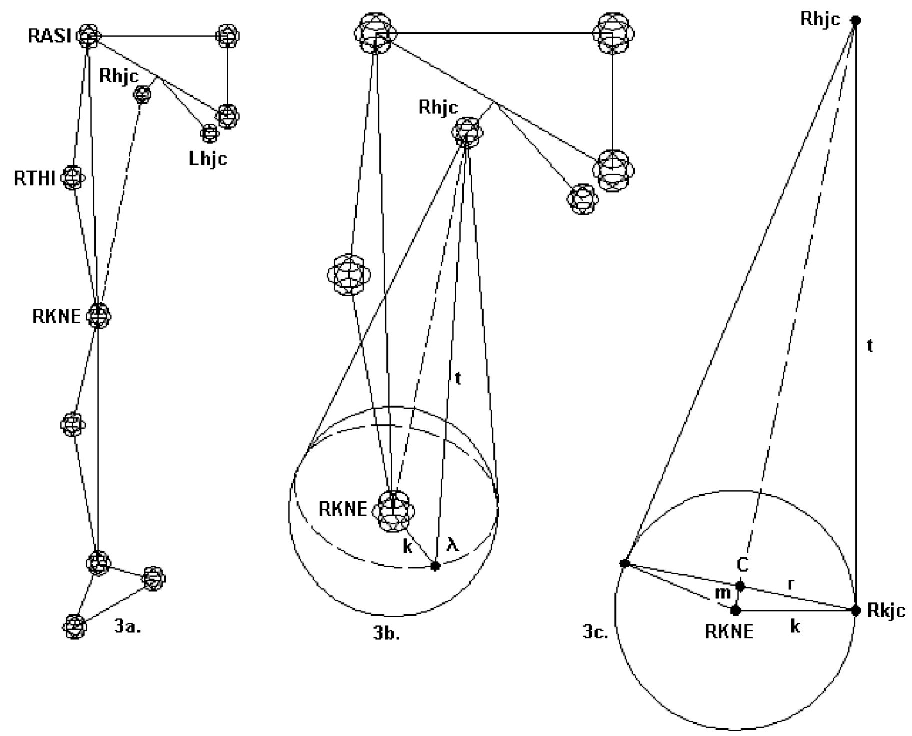


Figure 2.
Coordinates Systems:
4 local systems (thigh - left and right - and shank - left and right) were defined with addition of 8 markers. The Global Coordinate System was generated by the gait analysis system Vicon 370 and it is related to the laboratory space.

All definitions of the anatomic axis and joint centers assumed by the movement analysis system Vicon 370/VCM were maintained [1]. Thus, the position of the knee joint center, in relation to the coordinate system of the thigh, remains restricted to a region in the space determined by a circumference λ (C, r), as the model described in the figure 3.

[1] VCM User’s Manual, páginas 12 e 23:
- If a KAD is used, the knee flexion axis passes through the virtual knee marker, perpendicular to the segment joining the hip and knee joint centers, in the plane defined by the hip center, virtual knee marker and knee axis stick marker, irrespective of the placement of the thigh marker.
- The hip joint centers can be calculed using leg lenght, inter-ASIS distance, and na ASIS-greater trochanter distance calculed by a linear regression equation (Davis, Õunpuu, Tybursky and Gage (1991)).
- The knee joint center is located at one-half the knee width medially along the knee flexion axis.
- The hip-knee joint center axis is perpendicular to the knee flexion axis at the knee joint center, and these two axes define the frontal plane of the thigh.



Figures 3a, 3b, 3c:
Nomenclature:

- k : surface radius of the sphere with center in RKNE
  k = (knee width + marker diameter) / 2
- m : projection of k on the hypotenuse of the rectangle triangle Rkjc RKNE Rhjc
- C : circumference center λ
- r : circumference radius λ
- t : straight line segment tangent to the sphere
- Rhjc : hip joint center (Right)
- Rkjc : knee joint center (Right)
- λ: contact circumference of the straight line segment tangents to the sphere

Geometric determination of the knee joint center:

- Assumption:

"The knee joint center is located at one-half the knee width medially along the knee flexion axis."

- Geometrical space which satisfy the assumption:

Surface of a sphere with radius k = (knee width + marker diameter)/2 and center in RKNE.

Geometrical determination of the knee flexion-extension axis and the thigh longitudinal axis:

- Assumption:

"The hip-knee joint center axis is perpendicular to the knee flexion axis at the knee joint center..."

- Geometrical space which satisfy the assumption:

Contact circumference λ from the straight line segment tangents to the sphere.

Note:
Propriety of the tangent [2]:
1. All perpendicular straight line to a radius at its extremity of the circumference is tangent to the circumference.
2. All tangent to a circumference is perpendicular to the radius at the point of tangency.

Determination of the thigh frontal plane:

- Assumption:

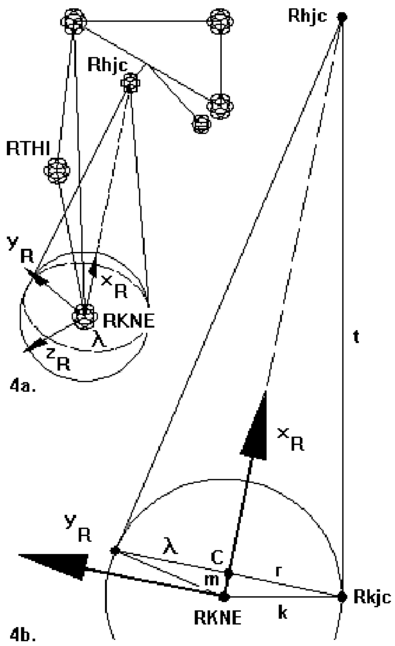
"The hip-knee joint center axis is perpendicular to the knee flexion axis at the knee joint center, and these two axes define the frontal plane of the thigh.".

- Geometric space that satisfy the assumption:

The determination of the unique point on the circumference λ, that represent all the possible solutions to the position of the knee joint center, needs, second the gait protocol used, a complementary reference: a anatomic point or derived from a kinematics analysis of the relative movement between the thigh and the shank [3].

2.3 Memorial calculus: Determination of the control variable

2.3.1 Auxiliary coordinates system (RKNE, x_R, y_R, z_R) (figures 4a and 4b)



Origin in RKNE.
Vectors:

$$x_R := \frac{Rhip - Rkne}{|Rhip - Rkne|}$$

$$y_R := Rthi - Rkne$$

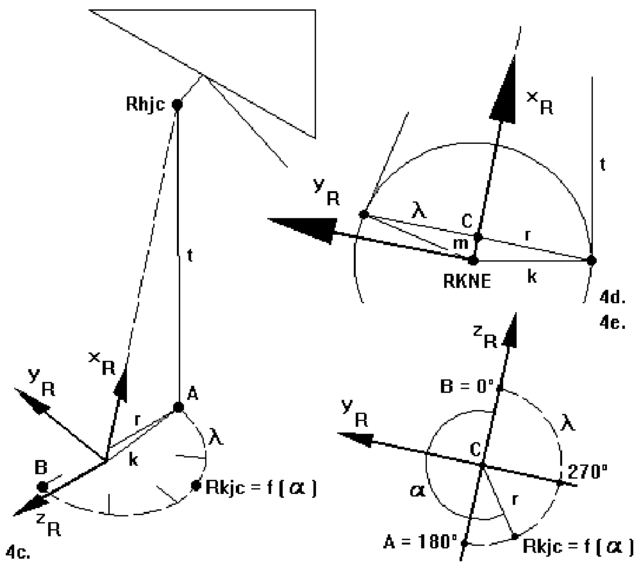
$$z_R := \frac{x_R \times y_R}{|x_R \times y_R|}$$

$$y_R := z_R \times x_R$$

[2] Dolce, O., Pompeo, J. N.: Fundamentos da matemática elementar – Vol. 9, 118:119.
[3] VCM User's Manual, page 32: Knee Alignment Device (KAD)
The alignment of the KAD stem with the knee flexion axis must be thoroughly checked. While the medial and lateral epicondyles of the knee provide a good approximation for the correct positions of the KAD pads in normal adult knees, in abnormally shaped knees, these landmarks may not represent the optimal positions for the pads. The sole criterion is that: over the flexion range of the knee which is used when the subject is walking, both the location and alignment of the KAD stem must move as little as possible relative to both the thigh and shank.

2.3.2 Localization of the circumference λ on the coordinates system (RKNE, x_R, y_R, z_R):

Center's coordinates C of the circumference λ and the knee joint center Rkjc, on the semicircumference AB (medial region of the right knee - figures 4c, 4d, and 4e).



Center C of λ:

$$C := \begin{pmatrix} m \\ 0 \\ 0 \end{pmatrix}$$

Where:

$$hipotenusa := |Rhip - Rkne|$$

Thus:

$$m := \frac{k^2}{hipotenusa}$$

$$r := \sqrt{k^2 - m^2}$$

The coordinates of the right knee joint center, Rkjc, were determined in 181 distinct points, in constant intervals of 01 degree - second the variation of the angle α ($180° \le \alpha \le 360°$) - on the semicircumference AB. Thus, the general equation of the right knee joint center is the follow:

$$Rkjc = f(\alpha) \quad \text{(figure 4e)}$$

$$Rkjc := \begin{pmatrix} m \\ r \cdot \sin(\alpha) \\ r \cdot \cos(\alpha) \end{pmatrix}$$, were $180° \le \alpha \le 360°$,
for $\alpha = 180°$ to $\alpha = 360°$, step = 1
or (α = 180°, 181°,...,359°, 360°)

2.3.3 Vector of knee flexion-extension:

In the auxiliary coordinates system (RKNE, x_R, y_R, z_R) was determined 181 vectors, entitled vectors of knee flexion-extension (V_f), second the angle α variation:

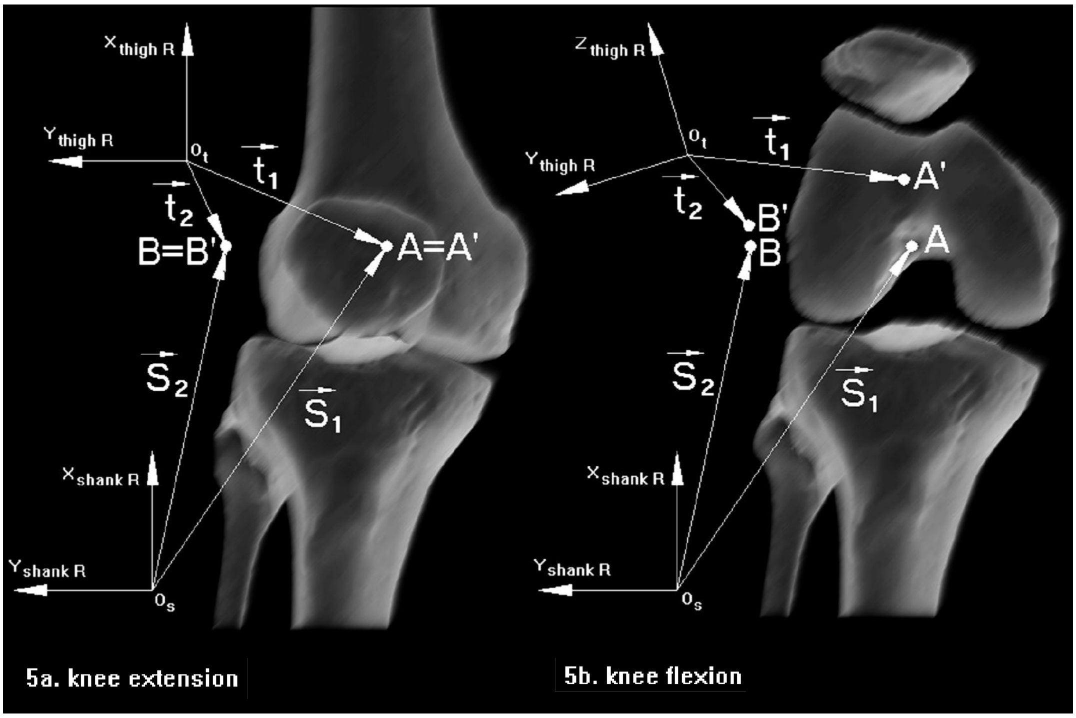
V_f = f(α)
V_f = (Rkjc - RKNE)

2.3.4 Control variable

Two static trials, supplementary to the standard protocol of the gait test, were realized. The first, as reference, with the subject on the orthostatic position, and in sequence other, with the subject sitting on a seat which height was almost the length of the shank's subject, to produce a flexion of about 90° in the knee joint. Only in these two trials the Helen Hayes Marker Sets was used with the increase of 8 markers (figure 1) - these additional markers aided in the direct generation of 04 locals coordinates system (thigh and shank, left/right) (figure 2), without the necessity use of anatomic points estimated, as the hip joint center, for example.

Sequence of calculation:

a. Initial reference position (1): Static trial with the subject in the orthostatic position - almost complete extension of the knee (0°) (figure 5a).



Figures 5a, 5b:

Nomenclature:

- A and A' = Rkjc, in the coordinates systems of the shank and thigh, respectively
- B and B' = RKNE, in the coordinates systems of the shank and thigh, respectively
- t1: position vector of point A' in the coordinates system of the thigh
- t2: position vector of point B' in the coordinates system of the thigh
- s1: position vector of point A in the coordinates system of the shank
- s2: position vector of point B in the coordinates system of the shank

b. Coordinates transformation of 181 vectors of knee flexion-extension (V_f = f(α), V_f = (Rkjc – RKNE)) from the auxiliary coordinates system (RKNE,x_R,y_R,z_R) to the local coordinates systems of the thigh and shank, respectively (Ot, Xthigh R, Ythigh R, Zthigh R) and (O_s,$X_{shank\ R}$,$Y_{shank\ R}$,$Z_{shank\ R}$). Vectors position: t1, t2, s1 and s2 (figure 5a).

c. Final position (2): Static trial with the subject sitting - approximate flexion of the knee joint = 90° (figure 5b). As result, the local coordinates systems suffer displacements (rotations and translations) in relation to the initial position (orthostatic position). The points A, A’, and B, B’, rather coincident, will present differences, due the loads and biomechanics characteristics of the knee joint (joint with 6 degree of freedom). Two distinct vectors of knee flexion-extension will be generated.

d. Coordinates transformation of the position vectors s1, s2, t1, and t2 of the points A, B, A’, B, and B’ respectively, from the local systems (thigh and shank) to the global system of coordinates (the laboratory coordinates system).

e. Determination of the angle between the vectors of knee flexion-extension (γ, being γ = f(α), 181 pair of vectors):

$$\gamma := \arcsin\left[\frac{\left|(t1 - t2) \times (s1 - s2)\right|}{\left|t1 - t2\right| \cdot \left|s1 - s2\right|}\right]$$

f. Variation of γ = f(α):

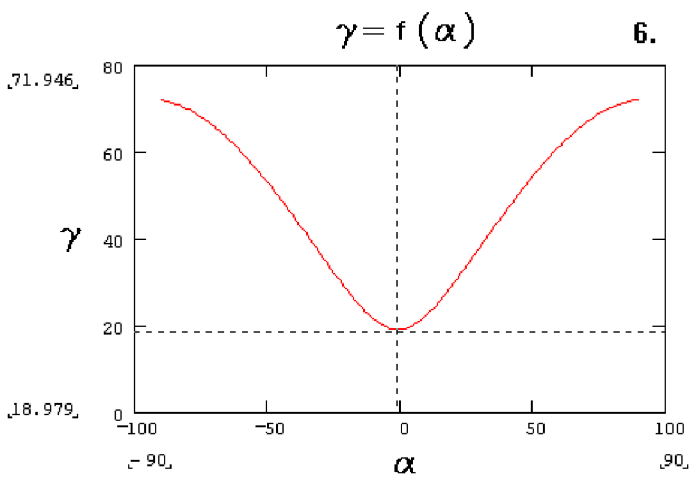


Figure 6: Characteristic curve of the function γ = f(α).

g. Control variable:

Control variable was defined as the minimal value of the angle γ (figure 6), and the respective rotation angle α. Thus, immediately, as described in item 2.3.2, the coordinates of the knee joint center are determined by the correlation to the rotation angle α.

2.4 Data acquisition and experiment.

Twenty three normal subject were submitted to the gait tridimensional analysis using the standard protocol, with utilization of the KAD. One static trial was collected with the KAD to determine the 4 offset angles by VCM: thigh rotation, shank rotation, static plantarflexion and static foot rotation [4]. Five dynamic trials were collected subsequently. To the Helen Hayes Marker Set were increased 8 markers, as described in figure 1.

Ten static trials were collected to calculate the control variable, rather the starting of the standard trial: alternating 5 trials with the subject on orthostatic posture and 5 trials with the subject sitting - flexion approximate of the knee joint = 90°, performed 25 combinations with the 2 postures (5x5=25) [5]. To each posture combination, were determined respectively the minimal value of the angle γ and the rotation angle associated α. The final sequence of calculation was realized using the rotation angle α average to the sample of 25 combinations. All the 4 offset angles were recalculated with the coordinates of the knee joint center determined by the angle α average. A second section was created on the VCM to reprocess the dynamic trials with the new value of the offset angles.

2.5 Statistical data analysis:

2.5.1 Sample of 23 normal adult subject analyzed in this work:

Patient No.	gender	age	Patient No.	gender	age
m_k1r	f	34	m_kad13	m	31
m_k2r	m	23	m_kad14	f	21
m_k3r	m	37	m_kad15	f	20
m_kad4	f	30	m_kad16	f	20
m_kad5	f	22	m_kad17	f	21
m_kad6	f	24	m_kad18	f	22
m_kad7	f	28	m_kad19	f	21
m_kad8	f	35	m_kad20	f	23
m_kad9	f	22	m_kad21	m	31
m_kad10	m	27	m_kad22	f	23
m_kad11	m	31	m_kad23	f	21
m_kad12	m	31			

[4] VCM User's Manual, pages 12, 13 and 14.

[5] Supplementary statistic analysis was realized to determine the minimal number of static trials necessary, or combinations of 2 postures (item 2.5.3, f).

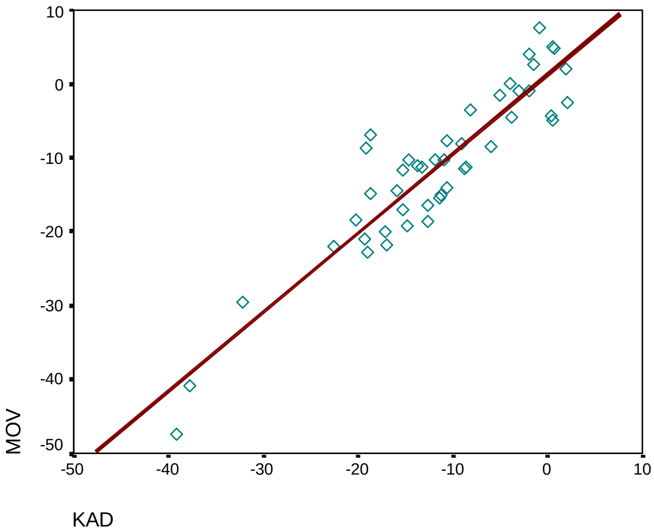
2.5.2 Offset angles (Thigh Rotation) determined by the standard gait protocol (KAD) and by the control variable.

Offset Angles: Thigh Rotation				
	Control Variable		KAD	
Subject	Left	Right	Left	Right
m_k1r	-3.56	-11.71	-8.2	-15.2
m_k2r	-8.62	4.12	-19.1	-1.9
m_k3r	2.57	-1.01	-1.5	-3
m_kad4	4.86	-0.94	0.7	-1.9
m_kad5	-29.61	-47.42	-32.2	-39.1
m_kad6	7.6	-6.86	-0.9	-18.7
m_kad7	-8.02	-4.28	-9	0.4
m_kad8	-15.43	-10.21	-11.4	-11
m_kad9	-21.77	-14.05	-17	-10.6
m_kad10	-18.37	-2.5	-20.2	2.1
m_kad11	-1.47	4.94	-5	0.5
m_kad12	-14.88	-10.17	-18.7	-11.8
m_kad13	-11.17	-11.26	-8.6	-13.2
m_kad14	-4.82	-11.42	0.5	-8.8
m_kad15	-18.52	-19.94	-12.7	-17.1
m_kad16	-10.23	-8.49	-14.6	-6
m_kad17	-19.12	-11.08	-14.8	-13.7
m_kad18	0	-14.51	-3.9	-15.9
m_kad19	-16.35	-21.03	-12.7	-19.3
m_kad20	-7.6	1.96	-10.6	1.9
m_kad21	-40.83	-21.96	-37.8	-22.5
m_kad22	-17.07	-4.55	-15.3	-3.8
m_kad23	-22.77	-15.13	-19	-11.3

2.5.3 Statistics tests: Correlation's analysis between offset angles determined by the gait standard protocol (KAD) and by the control variable. (by Simone Schenkman - statistical expert)

a. Non-parametric correlation of Spearman (graphic 1)

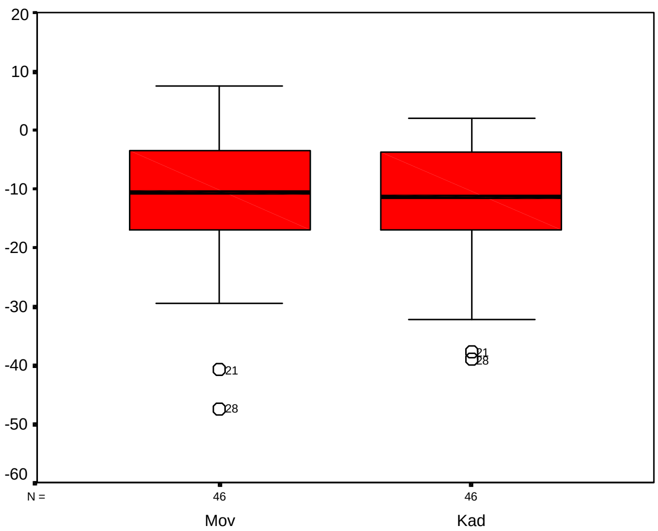
It was realized non-parametric correlation, because the data didn't present a symmetric distribution. The Spearman's correlation coefficient (LEVIN, 1981) - measure the correlation between two variables minimally ordinary. It varies from 0 to 1 (in module), as more near of 1, more perfect is the correlation. The value of rho (coefficient) was 86.5%, with $p < 0.001$.



graphic 1: Spearman's Non-parametric correlation
Offset angles: KAD and Mov (Control Variable)

b. Concordance between the KAD and the control variable (graphic 2)

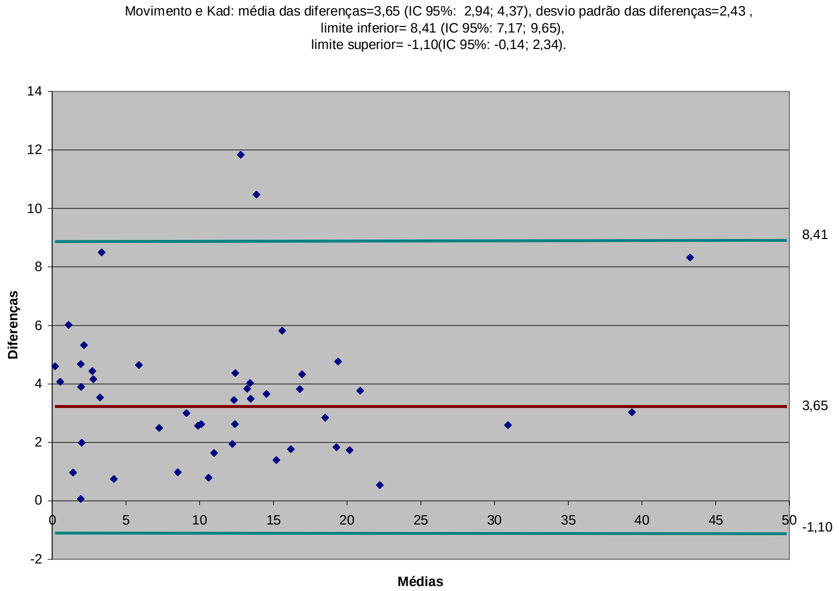
The Cronbach's alpha coefficient (STREINER & NORMAN, 1989) measure the internal consistency, concordance or the reproductivity of a test. It varies from 0 to 1, measuring the capability of the instrument in to distinguish the subjects. It corresponds to the quotient of variability between the subjects, in relation to the total variability (between subjects and systematic error). The alpha coefficient was 95.31% with $p < 0.0001$ and confidence interval from 91.65% to 97.43%, resulting in a excellent concordance.



graphic 2

c. Method of BLAND & ALTMAN (graphic 3)

This method allow to study with more detail the correlation's, visualizing the average of the offset angles determined by the KAD and by the control variable in contraposition to the absolute differences between these values. As didn't have association between these two measure, notice that the methods are valid between themselves.



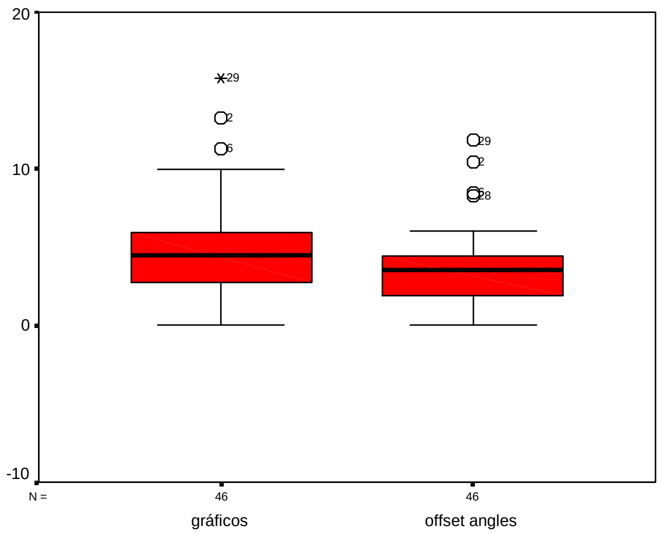
graphic 3: Averages and Differences
Movement and Kad: average of the differences = 3.65 (IC 95%; 2.94; 4.37),
standard deviation of the differences = 2.43,
upper limit = 8.41 (IC 95%; 7.17; 9.65),
lower limit = -1.10 (IC 95%; -0.14; 2.34).

d. Test of Wilcoxon

Test of Wilcoxon (SIEGEL, 1981): It is used to compare two dependent samples, or two subsamples of the same subjects, through out the time, intending to study if the subsamples have showed analogous distribution, taking the median as reference.
It was realized to compare the pairs value determined by the KAD and by the control variable, resulting in the value of p = 0.735, thus, any difference noticed in each pair was due to the hazard (73.5% of probability of the hazard be operating).

e. Comparison between the final graphics of the Hip Rotation and the values of the respective offset angles (graphic 4):

The medians observed were very similar: to the graphics were of 4.53 (0.06 - 15.82) and to the offset angles were of 3.51 (0.06 - 11.84).



graphic 4

Applying the confiability coefficient (alpha) the value was 98.14%, with $p < 0.0001$, resulting in a excellent concordance between the two methods.

f. Analyze of the 25 combinations of static's trials to calculate the control variable (figure 7/graphic 5).

The distributions of the 5 subsets from each individual were compared, to aid in the decision of how many combinations would be the minimal necessary to evaluate the subjects.

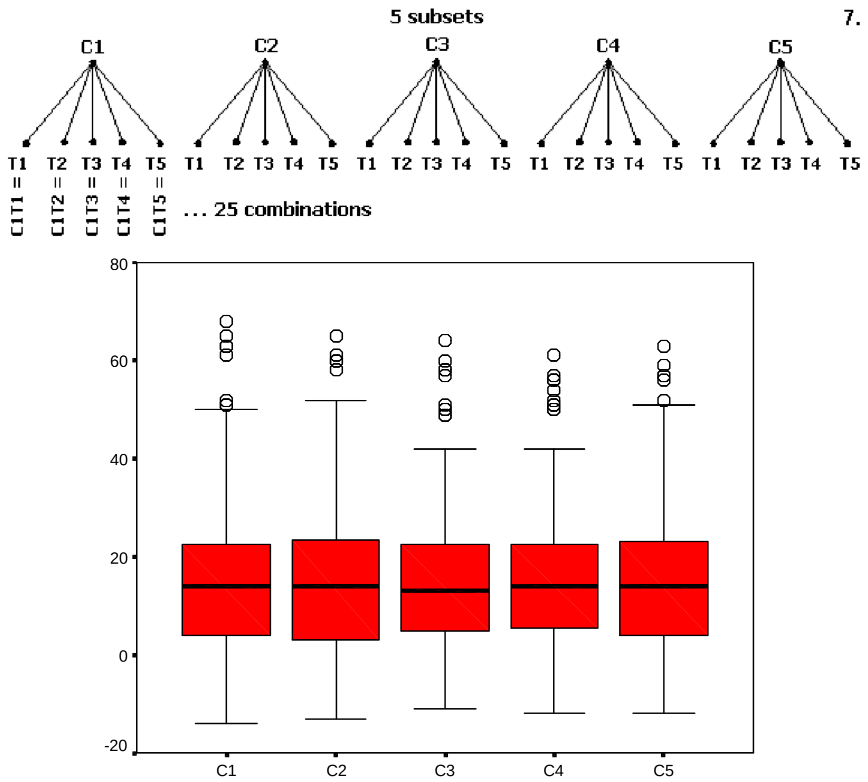


Figure 7/graphic 5: 5 subsets (C1, C2, C3, C4, C5) of combinations.

	C1	C2	C3	C4	C5
Median	14.00	14.00	13.00	14.00	14.00
Minimal	-14	-13	-11	-12	-12
Maximum	68	65	64	61	63

The distributions were very similar of the 5 subsets of combinations.

The confiability measure analysis, by the alpha coefficient of Cronbach, resulted in 99.88%, with $p < 0.0001$ (Confidence interval of 95% from 99.85% - 99.90%). When removed anyone of the subsets, the alpha value remained between 99.84 - 99.86%, thus there wasn't any change in the total value, it proves that only one subsets may be realized, because all of them are detecting the same measure.

Confiability analysis of pair to pair resulted in values between 99.58% to 99.78%, with values of $p < 0.0001$, confirming that only one combination of posture is enough to calculate the control variable.

3. References

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- A comparison of hip and knee kinematics when using a knee alignment device and Dynakad in normal children
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& Molly P. Nichols†
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- A new approach to determining the hip rotation profile from clinical gait analysis data
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† Department of Mechanical and Manufacturing Engineering, The Queen's University, Belfast

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†Departamento de Engenharia Mecânica da Pontifícia Universidade Católica do Rio de Janeiro

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4. Appendix

Comparatives graphics of the gait analysis realized in the sample of 23 subjects.

Legend:

______________ standard gait protocol (KAD)
______________ control variable