A KINEMATICALLY CONSTRAINED METHOD FOR DETERMINING SUBJECT SPECIFIC JOINT PARAMETERS

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INTRODUCTION

Joint centers and axes of rotation, referred to here as "joint parameters", are fundamental elements of quantitative gait analysis. Joint parameters derived in the traditional manner are influenced by significant random and systematic errors [Leardini 1999]. In this study we present a new method for determining joint parameters, based on the application of kinematic constraints. The functional method is the most well known alternative method for locating hip centers. Imaging studies and simulations have shown the functional method to be accurate [Leardini 1999, Piazza 2001]. However, recent data indicate that the functional method's variability may be unacceptably large for clinical gait analysis [McDermott 2001]. The functional method is also limited by its restriction to spherical joints, thereby excluding hinge-like joints such as the knee. The results of this study show that the kinematically constrained (KC) method is repeatable and objective for the estimation of both hip and knee parameters.

METHODS

Assume the point **q** is a joint center, and is therefore shared by adjacent segments. A motion that maps the segments from time t_k to time t_l satisfies the kinematic constraint,

$$\left(\mathbf{T_p} - \mathbf{T_d}\right)\mathbf{q} = \mathbf{T_p}\mathbf{O_p} - \mathbf{T_d}\mathbf{O_d} + (\tilde{\mathbf{O}}_\mathbf{d} - \tilde{\mathbf{O}}_\mathbf{p})\,. \quad (1)$$

$\mathbf{T_{p,d}}$ describe the re-orientation of the adjacent segments during the interval, while $\mathbf{O_{p,d}}$ and $\tilde{\mathbf{O}}_\mathbf{p,d}$ are the segment origins at the interval's end-points. The axis of rotation $\mathbf{L}_{kl}$, passing through **q** at t_k is found using the singular value decomposition theorem. By choosing a second interval with the same starting time, (t_k, t_m), a second axis of rotation can be found ($\mathbf{L}_{km}$). The joint center $\mathbf{q}_k$ at time t_k is the mutual intersection of all such axes; determined by first finding the intersections of each pair of axes, and then finding the mode of these pair-wise intersections [Fig. 1]. The average axis of rotation is defined as the mode of the instantaneous axes.

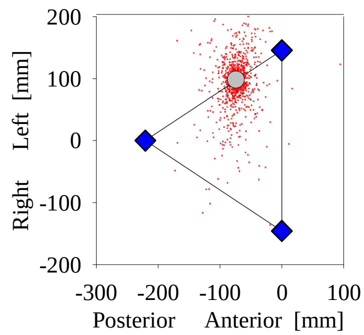

Figure 1. A transverse plane view of the Pelvis (diamonds are the L/R ASIS and PSIS). The KC based hip center (circle) is located at the mode of the of pair-wise axis intersections (dots).

Repeatability and objectivity were evaluated using a single healthy adult. The subject donned a standard clinical marker set with additional markers on the thigh and shank that permitted four independent segmental coordinate systems (CS) to be defined. During each session, 10 hip-centering trials (bi-lateral circumduction) and 10 knee-centering trials (flexion-extension) were conducted. Hip centers were calculated using one pelvic CS and four thigh CS. Knee centers and average knee axes were calculated using four thigh CS and four shank CS.

Table 1: Trial-to-Trial Variation: Repeatability

	H_X	H_Y	H_Z	K_X	K_Y	K_Z	Θ_X	Θ_Y	Θ_Z
			[mm]					[deg]	
Mean	-60.2	73.1	-94.1	14.3	18.9	-12.6	84.4	6.2	92.0
SD	3.6	2.3	3.7	3.1	14.8	0.6	1.1	0.9	1.0
Range	12.4	7.1	12.1	9.3	43.2	1.4	3.5	2.6	2.8

Table 2: CS-to-CS Variation: Objectivity

	H_X	H_Y	H_Z	K_X	K_Y	K_Z	Θ_X	Θ_Y	Θ_Z
			[mm]					[deg]	
SD	0.6	0.7	1.5	2.6	9.6	1.4	0.4	0.6	0.8
Range	1.5	2.0	4.3	8.3	41.8	4.3	0.9	1.5	2.1

RESULTS

Hip centers are expressed in the Pelvic CS: Orig. = mid-ASIS, (X,Y,Z) = (ant, lat, sup). Knee parameters are expressed in the Thigh CS: Orig. = mid-condylar, Y = bi-condylar axis (lat), (X,Z) ≅ (ant, sup). Trial-to-trial variations in joint parameters were calculated to assess repeatability [Table 1]. Within trial variations, due to choice of coordinate system (CS-CS), were calculated to measure objectivity [Table 2]. For the CS-CS data, SD and range were calculated for each trial over all CS-CS combinations, and then averaged over the 10 trials.

DISCUSSION

The joint parameters derived with the kinematically consistent method are repeatable and objective. The medial lateral position of the knee center (K_Y) is not well localized by the KC method (1.5 cm SD, 4cm total range). The objectivity data indicate that CS-CS outliers contribute to the high K_Y uncertainty (Range/SD > 4.0). In contrast, the knee axis is well defined. Thus, a hybrid of KC and traditional methods could be used to better locate K_Y. The objectivity and repeatability results suggest that inter-observer consistency should be similar to the inter-trial results. This has been seen in an earlier study [Schwartz 2001]. Further trials are currently being analyzed to re-confirm this hypothesis. The experimental design does not allow for a direct evaluation of accuracy (*e.g.* RSA, MRI). Indirect measures, including comparisons with regression based hip centers, the mid-condylar point and the bi-condylar axis, are favorable.

REFERENCES

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