Kinematically Constrained Joint Parameters I: Method, Repeatability and Objectivity

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Introduction:

Joint centers and axes of rotation (joint parameters) are fundamental elements of quantitative gait analysis. Joint parameters derived in the traditional manner contain significant random and systematic errors. The most prominent alternative approach, called the "functional method", defines the hip center from a sphere that best fits the motion of thigh markers relative to the pelvis [2]. The functional method has been shown to be accurate, however, recent studies suggest that its variability may be unacceptably large for clinical gait analysis [1]. The functional method is also limited by its restriction to spherical joints, thereby excluding hinge-like joints such as the knee. In this study we develop a method for determining joint parameters based on a rigorous application of kinematic constraints. The method is demonstrated on two healthy adults. The results show that the kinematically constrained (KC) method is repeatable and objective for the derivation of both hip and knee parameters.

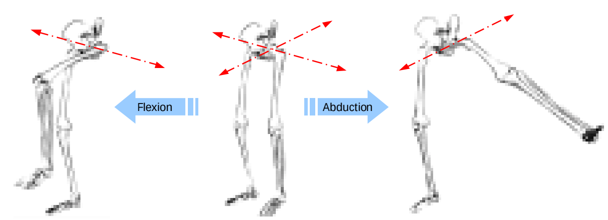
Analytical Methods:

- Consider three distinct body configurations measured as three different "samples" of motion data (samples i, j and k) [Fig. 1].
- Let **q** be the joint center, which is the unique point shared by adjacent segments. Then **q** satisfies the kinematic constraint:

$$(\mathbf{T}_p - \mathbf{T}_d)\mathbf{q} = \mathbf{T}_p\mathbf{O}_p - \mathbf{T}_d\mathbf{O}_d + (\mathbf{O}_d - \mathbf{O}_p) \qquad \text{(eqn. 1)}$$

- In equation 1, $\mathbf{T}_p$ and $\mathbf{T}_d$ are transformation matrices describing the re-orientation of the adjacent segments, while $\mathbf{O}_p$ and $\mathbf{O}_d$ are the origins of the segments.
- Using equation 1, compute the instantaneous axis of rotation for the motions i→j and i → k.
- For N samples of data, there are N*(N-1)/2 such axes. The joint center is defined as the mutual intersection of these axes [Fig. 2]. There is no unique mutual intersection due to limits in system and numerical accuracy, soft tissue motion and joint idealization (e.g. hip as a pure revolute joint).
- To define an effective joint center, find the intersections of each pair of axes O(N^4 solns.), then find the mode of these "pair-wise" solutions [Fig. 3].

Figure 1.



sample j sample i sample k

Figure 1 (above). For each pair of configurations (i-j, i-k) there is an instantaneous axis of rotation (red lines). These axes intersect at a shared point on the pelvis at sample i.

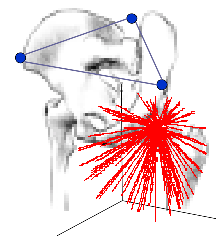


Figure 2 (left). Instantaneous axes (red lines) from all pairs of body configurations are transformed to a common local coordinate system. The mutual intersection of the instantaneous axes is the joint center. The pelvic markers are indicated by blue circles.

Statement of Clinical Significance:

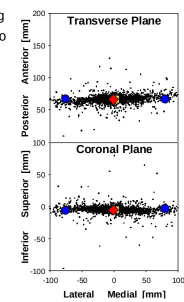
Hip and knee joint parameters that are repeatable and objective can be determined using a new Kinematically Constrained Method

Experimental Methods:

To evaluate the repeatability and objectivity of the KC method, two healthy adults were tested on three different days by four physical therapists. The subjects donned a standard clinical marker set with an additional markers on each thigh and shank. The additional markers allowed four different coordinate systems (CS) to be defined on each segment. These multiple CS were used to show that the KC method was indifferent to marker location (**objectivity**). During each session, two hip-centering trials (simultaneous bi-lateral hip circumduction *via* pelvic motion) and three knee-centering trials (passive flexion - extension) were conducted to assess **repeatability**. Hip centers were calculated using 1 marker-based pelvic CS and each of 4 marker-based thigh CS. Knee centers and average knee flexion axes were calculated using 4 thigh-based CS and 4 shank-based CS for a total of 16 CS-CS combinations.

A second set of experimental data were gathered to further evaluate repeatability. In this experiment, one subject was tested one time by each of 4 physical therapists. During each test, 10 hip-centering and 10 knee-centering trials were carried out. This design allowed for a more thorough investigation of trial-to-trial repeatability as well as a confirmation of the objectivity and results obtained in the first experiment.

Figure 3. **Validation**. An initial validation was performed using a mechanical analog of a knee joint. The analog consisted of two rigid wooden boards (1.5"x5.25"x18") connected by a consumer grade door hinge with approximately 5 mm of clearance. The analog allowed a total varus-valgus motion of 10°, internal-external rotation of <5° and medial lateral sliding of 5 mm. The termini of the hinge-pins were identified with reflective markers (blue circles) to allow the calculation of a true geometric hinge-axis and hinge-center (yellow square). The The hinge was then flexed and extended for five seconds, simulating the knee-axis trials described in the methodology. The data was processed using the standard KC algorithm. The KC-derived center (red diamond) was found to be within 3 mm of the true center. The KC-derived axis was within 3.7° of the true axis.



Results:

•Trial-to-trial differences in joint parameters were calculated to assess repeatability [Table 1, Fig. 4-5].

•Differences in parameters due to the choice of markers (CS-CS) were calculated to measure the objectivity of the KC method [Table 1, Fig. 4-5].

Table 1: Repeatability and Objectivity

		Ant/Post	Med/Lat	Sup/Inf
Trial-Trial Repeatability	ΔHC [mm]	3.3 (2.1)	5.7 (5.4)	5.3 (4.4)
	ΔKC [mm]	2.2 (2.6)	9.5 (11)	2.3 (1.8)
	ΔKA [deg]	2.0 (3.2)	3.0 (4.8)	2.8 (2.6)
CS-CS Objectivity	HC [mm]	(0.52)	(1.4)	(1.8)
	KC [mm]	(1.8)	(9.8)	(2.0)
	KA [deg]	(1.5)	(0.67)	(2.2)

Table 1 shows results from the first repeatability/objectivity experiments.

The trial-to-trial data show hip center repeatability on the order of 3 mm.

The anterior/posterior and superior/inferior knee joint center positions can be found within 3-6 mm.

The medial lateral knee center is the least repeatable parameter. This parameter can be located within +/- 10 mm.

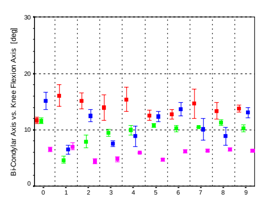
The very low standard deviations in the CS-to-CS results confirm that the method is objective. In other words, the location of markers does not influence the results

Figure 5. Knee Axis Results. The figure shows the angle between the palpated bi-condylar axis and the computed knee flexion axis for 1-subject, 10-trials and 4-physical therapists. Each square is a trial mean (all CS-CS combinations) and the error bars represent the 95% confidence interval of the mean.

The trial-to-trial repeatability (**total range**) is ± 4.5° from the session mean for a given tester. The CS-to-CS variability (objectivity) is significantly smaller.

Inter-session differences primarily reflect the variability in condylar palpation and marker placement. The variability in palpation has been estimated to be on the order of 6° [2]. It is important to note that these difference do not effect the kinematic and kinetic data derived from the method. This highlights one of the principal strengths of the KC method:

segmental coordinate systems derived from KC joint parameters are independent of maker locations.



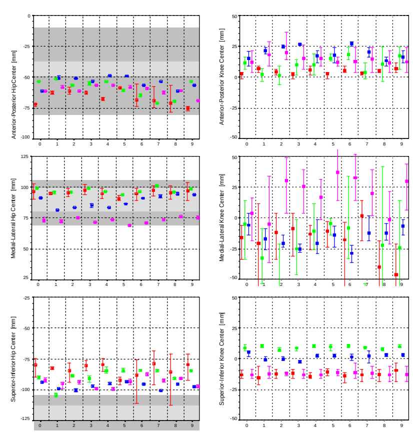


Figure 4. Hip and Knee Center Repeatability and Objectivity. The figures show the hip and knee center locations for a single subject, tested 10 times by 4 different physical therapists. Each square represents the **MEAN** value for a given trial. The error bars are the **MAXIMUM** and **MINIMUM** over all coordinate systems (not the standard deviation). Different colors represent different physical therapists (sessions). The variability in the regression-based hip centers due to anthropometric measurement variations is shown in light grey. The variability in the regression-based hip centers due to inherent uncertainty in the regression equations (±2**σ**) is substantially larger (dark grey).

Discussion and Conclusions

Joint centers and axes of rotation (joint parameters) are fundamental elements of quantitative gait analysis. Joint parameters derived in the traditional manner, using regression equations and alignment devices, are subject to significant systematic and random errors. A new approach, called the Kinematically Constrained Method, provides a practical method for laboratories to calculate objective and repeatable joint parameters.

The accuracy of the KC method has not been directly assessed, however the indirect evidence is promising. This evidence includes the comparison of hip centers to regression-based values, comparison of the knee axis to the bi-condylar axis, comparison of the knee center to the mid-condylar point and application of the model to a demanding mechanical analog with a nearly uniaxial distribution of instantaneous axes. In part II of this study, lower extremity kinematics are calculated using the KC-based parameters in a repeated-measures study.

The variability of the medial-lateral component of the knee joint center is significantly higher than that of the other joint parameters. A potential methodological solution to this issue is to define the knee center using the other two components (AP, SI), along with the calculated knee flexion axis and measured knee diameter.

The KC method is one of several approaches that aim to improve the objectivity and accuracy of gait analysis [1- 6]. It is not yet clear which of these methods (if any) is the best. The *de facto* selection of any one method without a careful evaluation of the competing methods must be avoided to assure optimal gait analysis systems in the future.

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