Validation of a Protocol for Motion Analysis

Michael M. Collins, McNair Scholar, Virginia State University

Faculty Research Adviser
Stephen Piazza, PhD, Assistant Professor
Departments of Kinesiology, Mechanical Engineering, Bioengineering, Orthopedics and Rehabilitation
Pennsylvania State University

Research Assistant
Prashant N. Bansal
Pennsylvania State University

1. Introduction

Gait analysis is the systematic measurement, description, and assessment of those quantities thought to characterize human locomotion (3). Through gait analysis, kinematic, kinetic, electromyographic, and spatio-temporal data are acquired and analyzed to provide information that is ultimately interpreted by clinicians to form an assessment or used by researchers to develop new treatments and expand the knowledge base. Current examples of gait analysis include: (i) the assessment of cerebral palsy locomotion to assist in the surgical or orthotic intervention, (ii) the progressive examination of neuromuscular diseases such as Parkinson's or muscular dystrophy, (iii) the quantification of the effects of orthopaedic surgery through the comparison of pre- and post-operative patterns, (iv) and virtual reality, movies, and video games.

Quantitative gait analysis using three-dimensional motion analysis systems is becoming common practice in many research laboratories. Reliability is of the utmost importance, especially when clinical decisions are made, or in research such as product design and development. For the results of any motion analysis to be valid and widely accepted, thorough examination of reliability and error associated with the measurement procedure are required (6). The purpose of this research was to first standardize the gait analysis protocol for the Center for Locomotion Studies at the Pennsylvania State University. Subsequently, we investigated the intra-rater and inter-rater repeatability of kinematic data utilizing the VICON 370 (version 2.5) 3D motion analysis system. Having a reliable and valid protocol will be the groundwork for many subsequent studies that will be dependable and more widely accepted.

2. Literature Review

There have been several significant studies that have investigated the reliability of different motion analysis systems. However, the reported results have not been altogether consistent.

M.P. Kadaba et. al. (2) investigated the repeatability of gait variables including kinematic, kinetic, and electromyographic data waveforms and spatiotemporal parameters. Forty normal subjects were evaluated three times a day on three separate test days while walking at their preferred or normal walking speeds. Three-dimensional trajectories of body surface markers for computing joint angle motion were acquired using a computer-aided motion analysis system (VICON, Oxford Metrics Ltd., Oxford, England). While the subject walked in the positive X direction on a 6 m walkway, at least four of the five infrared cameras recorded the trajectories of markers on one side of the body. The opposite side of the body was subsequently recorded as the subject walked in the negative X direction

Retroreflective markers were applied to the shoulders (acromion process) and to the anterior superior iliac spines (ASIS). Key locations on the lower extremities include the lateral aspect of the greater trochanter, the knee joint line (posterior to the lateral femoral condyle), the lateral malleolus, and the dorsum of the foot between the second and third metatarsals. Attached to the pelvis was a posterior sacral wand (8 cm long) to measure the orientation the pelvic tilt. Two lateral wands (7 cm long) were attached to the thigh, midway between the hip and knee joints, and the shank, midway between the knee and ankle joints. The purpose of this was to hopefully measure the rotation angles more accurately. The hip joint center was estimated using regression equations with the leg length as the independent variable. The knee center was assumed to lie in a plane defined by the HJC, thigh wand marker, and knee marker, halfway between the femoral condyles. The ankle joint center was assumed to be in a plane defined by the knee joint center, shank wand marker, and ankle marker one-half the distance between the malleoli. Euler angle definitions were used to compute three-dimensional rotations of the pelvis, hip, knee, and ankle.

The intrarater repeatability was excellent for kinematic data in the sagittal plane both within a test day as well as between test days. In the frontal and transverse planes, joint angle motion yielded good repeatability within a test day but poor between test days. M. P. Kadaba et. al. attributed the poor between-day repeatability of joint angle motion in the frontal and transverse planes partly to variation in the alignment of markers. However M. P. Kadaba et. al. concluded that, in general, the results demonstrate that with the subjects walking at their normal speed, the gait variables are quiet repeatable. Thus, suggesting that it may be reasonable to base significant clinical decisions on the results of a single gait evaluation.

Another study assessed the reliability of gait measurements, and quite interestingly resulted in different findings from the reported reliable M. P. Kadaba study. V. Maynard et. al. (6) investigated the intra-rater and inter-rater reliability of kinematic data using the CODA mpx30 (Charnwood Dunamics, Barrow on Soar, Leicestershire, England) motion analysis system. Using very similar methods to M. P. Kadaba et. al. to define the anatomical co-ordinate system, amongst other measurements, V. Maynard studied kinematic variables including hip, knee and ankle angles on initial contact, mid stance and mid swing.

Gait analysis was conducted on ten subjects twice each day, morning and afternoon, and once more a week later while keeping the investigators blind to the previous measurements. V. Maynard et. al. (6) used a standard protocol for marker placement and data collection with the hopes of reducing error. Their findings suggested a better inter-rater than intra-rater reliability for most of the gait parameters measured. Test-retest repeatability of measurements of joint kinematics was best for the knee angles and poorest for the hip angles. The findings reported do not demonstrate complete reproducibility of the gait analysis data when measurements were made with the CODA mpx30. The researchers attributed the poor reproducibility of kinematic data to the inaccurate placement of markers on the surface anatomical landmarks.

A similar study conducted by Cowman et al. (5) used the same CODA mpx30 motion analysis system, and obtained similar results. Their aims were to asses the degree of normal variation during the walking cycle and also the degree of error associated with marker placement as measured using the system above. They obtained two normal subjects (9 and 21 years) and assess them three times each by two chartered physiotherapists that were experienced in gait analysis. The subjects walked at an imposed speed, until four clean trials were collected. They observed high percentage error within the inter-rater data and it was believed that this may be attributed to the number of changing factors during an interpreter analysis. Furthermore, they interpreted this to mean that kinematic measurements at specific points in the cycle are less reliable that temporal and spatial data. A possible reason they offer for the poor reliability is the error associated with marker placement.

These studies have reported compromised kinematic data due partly to the misplacement of anatomical landmarks. A study headed by Ugo Della Croce et al. (4) investigated the reliability of the pelvis and lower limb anatomical landmark identification. The two healthy subjects investigated wore four skin marker cluster: on the pelvis, on the left thigh, shank and foot, each conveniently located in front of two cameras of a stereo-photogrammetric system (ELITE, B.T.S. Milan). To assess the intra- examiner reliability, the examiner (the Gait Laboratory physical therapist) was asked to identify the following sequence of: Left and Right, Anterior and Posterior, Superior Iliac Spines (LASIS, RASIS, LPSIS, LPSIS), Greater Trochanter (GT), Medial and Lateral Femoral Epicondyles (ME, LE), Tibial Tuberosity (TT), Head of the Fibula (HF), Medial and Lateral Malleoli (MM, LM), Calcaneous posterior surface (CA), dorsal aspects of First, Second and fifth Metatarsal head (FM, SM, VM). Additionally, the position of the Femur Head (FH) was assessed referring to the acetabulum center in the femur reference frame during the standing. According to the CAST protocol proposed by Cappozzo et al. (1995), a stick supporting two markers was used to point at each anatomical landmark, and a short static acquisition was performed. This anatomical landmark pointing procedure (calibration) was done six times consecutively. To assess the inter-examiner reliability, six registered physical therapists conducted the anatomical landmark calibration once on two subjects.

They reported that the anatomical landmark identification error is greater than the other sources of error. The inter-rater examiner test showed greater error than those obtained in the intra-rater examiner. Among the body segment anatomical reference frames, the one of the foot is the most difficult to locate. The researchers say that this is likely to cause very low reliability in assessing joint offsets.

In hopes of increasing the accuracy and reliability of kinematic data, T. F. Besier et al (1) aimed their experiment at investigating numerical method used to define joint centers and axes of rotation independent of anatomical landmarks (Als). To do this, they compare the repeatability of gait data obtained from two models, one base on Als, and the other incorporating a functional method to define hip joint centers and a mean helical axes to define knee joint flexion/extension axes (FUN model). They also developed a foot calibration rig to define the foot segment independent of Als. The results indicated that the FUN model produce slightly more repeatable hip and knee joint kinematic data than the AL model, with the advantage of not having to accurately locate Als. This is especially repeatable for subject populations where location of Als is difficult. Repeatability of the models was similar comparing within-tester sessions to between-tester sessions. The foot calibration rig employed in both the AL and FUN model provided an easy alternative to define the foot segment and obtain repeatable data, again without having to accurately locating Als on the foot.

3. Methods

3.1 Gait analysis protocol

Eight able-bodied subjects (18-35y; mean 24y) free of gait altering injuries participated in this study. Gait analysis was performed on each subject twice a day on two separate days. The two raters performed separate gait analysis each day for the inter-rater examination. The same was repeated for the second day for the intra-rater examination.

A seven-camera VICON 370 motion analysis system (Oxford Metrics, Oxford, UK) was used in conjunction with two force-plates to collect motion data. A standing trial followed by a subject calibration trial was collected to locate the Als and the axes of rotation for the knee and ankle. During each marker application session, the subject walked at their preferred or natural speed. A minimum of five successful data collection trials were captured. To determine the hip-joint center, a functional method similar to that used by Piazza et al. was employed, whereby the subject was required move the right, followed by the left, thigh through four circumductions, 2 flexion/extensions, and 2 ad- abductions.

3.2 Marker set and definitions of segment and joint coordinate systems

To determine the three-dimensional position and orientation of each lower limb segment, cluster of four retro-reflective markers were firmly adhered to the subjects sacrum, thighs, shank, and feet. A technical coordinate system (TCS) was defined using each thigh, shank, and foot segment clusters such that the anatomical coordinate system (ACS) and joint centers were defined relative to these TCSs. Markers were placed on the following anatomical landmarks: the lateral and medial malleolus, lateral and medial femoral epicondyles, and the left and right ASIS and PSIS.

The foot segment was defined by the subject aligning the 2^{nd} metatarsal heads and the heels of each foot on top of cardboard having 2^{nd} metatarsal head and the heel markers on it.

3.4 Statistics

Intra-rater and inter-rater reliability was assessed with the interclass correlation coefficient (ICC) method. This approach is an appropriate statistical method for studying agreement between sets of interval data. An ICC coefficient of greater than 0.75 was accepted as evidence of good agreement. ICCs of less than 0.75 were considered less than convincing or not very reliable.

4. Results

4.1 Intra-rater reliability

The intra-rater portion of the study analyzed the variation between one rater's results on any given subject. The results of the intrasubject repeatability are given in table 1. The ICC's for the hip flexion/extension were the best. Rater 1's ICC's were slightly better than rater 2's with averages of 0.64 and 0.56 respectively. The highest ICC for the intrasubject was the ankle minimum for rater 2 at 0.70. Interestingly, the ankle minimum ICC for rater 1 was –0.42. The knee minimum and maximums had the lowest averaged ICC at 0.13. This is probably a result of the subjects not having their knees locked during the standing trial.

4.2 Inter-rater reliability

The inter-rater portion of the study analyzed the variation between raters measurements with only one subject. Results for the inter-rater repeatability are given in Table 1. The single highest ICC was the knee minimum on day 1 at 0.83. However, on the same day the maximum ICC was calculated to be 0.27. The lowest ICC calculated was for day 2's knee maximum at –0.29. Again, this is more than likely due to subjects not being reminded to lock their knees. The ankle ICCs were the highest followed by the hip and then the knee. In terms of averaged ICC's, Day 1 was more successful than Day 2.

Table 1:ICCs

Table of Interclass Correlation Coefficients				
Parameters	*Day 1 Rtr 1 vs Rtr 2*	*Day 2 Rtr1 vs Rtr 2*	*Rater 1 Day 1 vs Day 2*	*Rater 2 Day 1 vs Day 2*
Pk. Knee Flexion	0.27	-0.29	0.05	0.00
Pk. Knee Extension	0.83	0.19	0.36	0.13
Pk. Ankle Flexion	0.65	0.33	0.34	0.42
Pk. Ankle Extension	0.58	0.24	-0.42	0.70
Pk. Hip Flexion	0.70	0.27	0.69	0.58
Pk. Hip Extension	0.61	-0.04	0.59	0.54

5. Discussion

The purpose of this study was to standardize the motion analysis protocol and determine its reliability by analyzing the inter- and intrarater repeatability. We assumed that a standardized protocol for marker placement and data collection would likely minimize errors due to the rater. Interestingly, our findings suggest a better intrarater that interrater repeatability for kinematic measurement using the VICON 370 system.

Inconsistent with some previous studies, we found better repeatability for the hip and worst for the knee. As stated earlier, this is probably a side effect from the subjects not having their knees locked. In future protocols, subjects will be reminded repeatedly to lock their knees when collecting the subject calibration trials. This would also increase the repeatability of the hip angles. However, the ICCs calculated are fair given a few limitations. One being the time allotted, the study was conducted in a fairly short amount of time. We believe that if the study were extended, there would have been better preparation. Also, there would have been fewer subjects tested per day which is believed would reduce fatigue in raters and subjects. Which brings us to the next limitation, which is the natural variation in individual's gait patterns. Considering the time it took to complete a subjects testing, 3 to 4 hrs, and subjects were affected by fatigue that in turn introduces increased gait variation.

Overall, we consider this to be a fairly successful study, given the limitations, and accept the proposed protocol as reliable, pending minor changes.

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