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Assessment of the kinematic variability among 12 motion analysis laboratories

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ABSTRACT

Variability of kinematic measurements among sites participating in a collaborative research investigation is a primary factor in determining number of subjects, level of detectable difference and statistical power of a multi-site research study. In this study, one subject was evaluated by 24 examiners at 12 motion analysis laboratories and the observed variability of nine kinematic parameters are reported. Following implementation of a standardized gait analysis protocol the same subject returned for another evaluation at each of the 12 laboratories. Additionally, system accuracy and variability of the subject within and between test days are included as factors that may affect between site variability. Marker placement among examiners is identified as the largest source of variability. A 20% decrease in variability was noted following implementation of the standardized protocol.

Three-dimensional motion analysis is commonly used to document pathologic gait for treatment planning, evaluation, and outcomes research in children and adolescents with cerebral palsy. Heterogeneity of pathology and individualized treatment of cerebral palsy have challenged the success of multi-center collaborative research. Furthermore, it can be difficult to obtain homogenous populations from a single or small number of sites to evaluate the effectiveness of treatment. These studies have been stymied by inconsistent kinematic and kinetic modeling protocols and questionable data compatibility between laboratories using differing hardware and software [1]. Recognizing these challenges, the Shriners Hospitals for Children Motion Analysis Laboratory network (SMALnet) began developing standardized data collection protocols for clinical gait analysis to enhance the capacity for collaborative studies [1]. The current study describes the variability among 12 SMALnet laboratories before and after implementing standardized data collection protocols.

In multi-center research designs, the source and magnitude of measurement error and variability are of concern, especially among examiners from different institutions [2]. Measurement errors and variability can come from three primary sources: (1) examiner, (2) measurement system, and (3) subject. Variability is defined by the sum of variances from each independent source [2,3]. Knowledge of variance is necessary for determining the number of subjects, level of detectable difference and statistical power in research studies.

Few published studies assess the variability of kinematic measures. Variability of a normal adult population within and between sessions with one examiner has been described by Kadaba et al. [4]. They found within-session variability to be low; one representative trial can generally be used for clinical decision making. In contrast, between-session variability was found to be much higher than within-session variability because of the high potential for marker placement differences. This makes reliable comparisons between sessions more challenging, even with one examiner. Such a study has not been replicated in the pediatric population.

Chambers and Goode [5] investigated the variability of kinematic measurements among five sites. More than 90% of the variability was from marker placement differences and minimal variability was attributed to system accuracy. Schwartz et al. [6] assessed within-subject, within-observer and between-observer differences within one laboratory, and revealed significant variability in transverse plane kinematics. Tirosh and Baker [7] have described a method of assessing and documenting between-examiner differences using a web-based data capture utility.

Between reviewer variability impacts the interpretation of gait analysis data. Skaggs et al. [8] assessed variability of interpretation of gait analyses from seven patients by 12 reviewers at six sites. The level of agreement for treatment recommendations among

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sites was only fair. Variability of the kinematic data among sites was not reported. Noonan et al. [9] confirmed these findings on 11 ambulatory patients with spastic cerebral palsy evaluated at four sites. They found the variability in the sagittal, coronal, and transverse plane kinematic motions to be 12°, 7° and 20° respectively, and treatment recommendations were highly variable.

Standardization has been shown to have a positive impact on variability. Kleissen et al. [10] examined the consistency of EMG patterns from 3 laboratories and concluded that standardization of instrumentation, protocols, and processing techniques successfully reduced between site variability. The variability of goniometric examination within and between examiners within individual facilities has been described [11–18]. McDowell et al. [19] attempted to minimize this variability with a training program. With a written, standardized protocol and training program, between day errors in ankle dorsiflexion and popliteal angle measured with a goniometer varied from 18° to 28° for multiple examiners compared to 5–7° for one examiner.

The purpose of this study was to evaluate sources and magnitudes of variability in kinematic measurements on one subject at 12 motion analysis laboratories. Four sources of variability were evaluated between: (1) examiners, (2) trials, (3) systems, and (4) days. In addition, the change in variability of the kinematic measures was recorded following the implementation of a standardized gait analysis protocol.

1. Methods

This project utilized a single subject design. The subject was a 25-year-old male, 170 cm height, 73 kg weight, 83 cm leg length with no previous orthopedic surgery and no diagnosed orthopedic, neuromuscular or neurologic conditions.

This study examined the magnitude and potential sources of between examiner variability. Examiner was defined as the individual(s) or team(s) who perform clinical kinematic assessments and might participate in a hypothetical multi-center research project. Examiners had a broad range of experience, from 6 months to 21 years, with an average of 5.0 years in gait analysis and 11.8 years in a clinical setting. The examiners included sixteen physical therapists, one physician, three kinesiologists, three biomechanists, and one technician. The outcome of interest was the overall variability in kinematic measures as reported by this population of examiners.

The subject was examined at 12 sites within a 3-month period. Ten sites utilized Vicon Motion Analysis data collection hardware and Vicon Clinical Manager software (VCM, Oxford Metrics, Oxford, UK). Two sites utilized Motion Analysis Corporation hardware and Orthotrak software (Motion Analysis Corporation, Santa Rosa, CA). The subject received a full kinematic assessment at each site by at least one examiner using the site's typical protocol.

After the subject was examined at each laboratory, a standardization process was undertaken through the development of several training videos describing a minimum standardized gait analysis protocol (MSGAP). These training videos were sent to each site involved in this study. Finally, this process concluded with a training session attended by staff from all 12 laboratories and discussion about protocols. Following implementation of the MSGAP, the same subject returned to each laboratory within a three month period one year after the first set of examinations for a second full kinematic assessment.

Ten kinematic trials were collected for each examiner during each visit. Data reduction was performed by the local laboratory staff using their customary methods. Kadaba et al. [4] suggested that differences in marker placement between testing sessions caused offsets to the level of the kinematic curves. That study showed that within-session reliability of kinematic data was quite high, and that the between-session errors were dramatically affected by marker placement error. For this study, mean joint angle was selected as an indicator of marker alignment between sites [4,20,21]. Although the shape of the curve may also be affected by differences in marker alignment, the mean value is a sensitive indicator of similarity between sessions and will reflect systematic differences. Mean pelvic tilt, pelvic obliquity, pelvic rotation, hip flexion, hip abduction, hip rotation, knee flexion, ankle dorsiflexion, and foot progression angle were recorded for each trial. The right side was arbitrarily selected for analysis.

Overall variability of the mean joint angle among examiners was calculated by averaging the means of ten repeated trials for each examiner and then calculating the variance for 24 examiners. Variability of the subject within session was calculated as the variance of the means of repeated trials within each session, then averaging the within-session variances across sessions. Analysis of variance (ANOVA) was used to evaluate differences between trials within session.

During the first visit an instrumented rod (MTD-1, Motion Lab Systems, Baton Rouge, LA) was used to confirm system accuracy. The rod was moved through the field of view of each laboratory and the distance between two markers was measured for one trial of ten seconds duration. The mean, standard deviation and average error of the measured distance over all frames in the trial were reported. The same rod was instrumented to simulate a right leg and pelvis with the conventional marker set, and was moved through the field of view of each laboratory. Mean, standard deviation, and maximum difference for hip flexion, hip rotation, knee flexion and ankle dorsiflexion were reported.

Following the first set of visits, the subject was evaluated on six consecutive days at one site to determine between-day variability. Five kinematic trials were captured each day. Marker locations were noted using permanent ink to ensure consistent placement between tests. Trials were processed using the same modeling options including identical estimates of pelvic width, pelvic depth, and tibial torsion. Mean values of each kinematic measure were recorded for each trial. Between-day variance was calculated by averaging the means of five repeated trials for each test day, and then calculating the variance over the 6 days. A repeated measures ANOVA was performed with factors of trial (five per day) and day (6 days).

2. Results

Mean joint angles, standard deviations, and range among examiners for each visit are shown in Table 1. Standard deviation of the mean joint angle for all examiners ranged from 1.2° to 7.3°. The range between examiners varied from 5.6° for pelvic obliquity to 28.3° for hip rotation, with an average maximum difference over all parameters of 14.8°. Following implementation of the MSGAP, the standard deviation decreased for 7 of the 9 kinematic measures by an average of 22%. Pelvic tilt and hip rotation showed increases of 4–8% in the standard deviation. The range between examiners decreased substantially for 8 of 9 kinematic measures by an average of 29%. Hip rotation showed an increase of 19% in the range.

The fixed distance and fixed angle tests, data from two laboratories could not be successfully processed, and a different configuration of markers was inadvertently used at three laboratories. The remaining seven sites were used for analysis. The average error in measuring the known distance between markers was 1.2 mm. The average standard deviation over all sites was 0.9 mm. The mean joint angles from each laboratory using the instrumented rod are shown in Table 2. The average standard deviation across sites was 0.5°. The maximum difference between measurements ranged from 1.4° to 1.9°.

Table 3 shows mean joint angles measured over six days for the subject at one site with consistent marker placement. No significant differences existed between trials within day. There were significant differences between days for five of eight measures (ANOVA, $p < 0.05$). The standard deviation across days ranged from 0.2° to 1.5°, with an overall average across all measures of 0.9°. The maximum difference in the mean joint angle

Table 1
The mean value of each kinematic measure from one subject examined by 24 examiners from 12 sites is shown along with the overall standard deviation from the first visit in 1999 and the follow-up visit in 2001. The range between the minimum and the maximum mean value for any examiner is shown.

Parameter	First visit			Follow-up		
	Mean	SD	Range	Mean	SD	Range
Pelvic tilt	5.2	3.5	14.8	4.5	3.8	13.9
Pelvic obliquity	0.3	1.2	5.6	0.3	1.1	3.6
Pelvic rotation	−2.1	1.8	7.2	−2.0	1.3	6.2
Hip flexion	9.9	5.0	23.9	10.7	4.4	17.1
Hip abduction	1.0	2.5	11.7	−1.5	2.3	9.4
Hip rotation	−5.0	7.3	28.3	−8.3	7.6	33.8
Knee flexion	20.0	4.8	18.4	24.4	3.0	9.3
Ankle dorsiflexion	0.9	2.7	12.0	4.2	1.9	6.1
Foot progression angle	−13.9	2.6	11.4	−14.0	2.2	7.8

Table 2
The mean and standard deviation of selected joint rotation angles (degrees) obtained from 7 sites by passing a mechanical rod instrumented with markers reflecting a typical configuration of the conventional gait model are shown. The range between the minimum and the maximum mean value for any site is shown.

Parameter	Mean	SD	Range
Hip flexion	26.6	0.7	1.9
Hip rotation	2.8	0.5	1.4
Knee flexion	12.2	0.5	1.4
Ankle flexion	−1.9	0.2	0.6

Table 3
The mean and standard deviation of one subject walking on 6 consecutive test days at one site with marker locations carefully marked between test sessions. The range between the minimum and the maximum mean value for any day is shown. The results of an analysis of variance (ANOVA) with trial and day as fixed factors are indicated. There were no significant differences between trials, but there were significant differences between days for 5 of the 8 parameters.

Parameter	Mean	SD	Range	Trial, p	Day, p
Pelvic tilt	2.4	1.5	4.2	.645	**.000**
Pelvic obliquity	−0.3	0.2	0.8	.449	.427
Pelvic rotation	0.1	0.5	1.2	.874	.356
Hip flexion	10.6	1.0	2.7	.217	**.000**
Hip rotation	−2.0	1.1	2.5	.960	**.000**
Knee flexion	23.9	0.7	1.8	.284	**.036**
Ankle dorsiflexion	0.2	1.1	3.1	.206	**.000**
Foot progression angle	−12.9	0.9	2.2	.174	.135

between days ranged from 0.8° to 4.2°. The average maximum difference between days across all measures was 2.3°.

Table 4 contains the relative magnitudes of the sources of variance examined. "Overall" represents the overall mean variance. "Between Days" represents variance due to repeated testing of the subject between days with consistent marker positions. "Between Systems" represents the variance attributable to the reliability of the system. "Within Session" represents the variance of the subject within one session. No significant differences existed between trials within test session for any joint angle (ANOVA, $p > 0.05$).

The relative proportion of the between-day, between system, and within-session variances to the overall variance are shown in Table 4. The proportion of variance attributable to the system based on a fixed geometric model was less than 2% of the overall variance. The proportion attributable to the within-session variance was 8% or less, except for pelvic rotation (26%) and foot progression angle (33%). Less than 18% of the overall variance was attributable to variability in subject performance between days. Less than 25% of the overall variance could be attributed to a combination of variance between days, due to the systems, or within sessions except for foot progression angle and pelvic rotation.

3. Discussion

This study was part of a standardization effort within the Shriners Hospitals for Children. The goal was to estimate the sources and magnitudes of kinematic variability for a hypothetical multi-center research project. Variability of kinematic measures from 24 examiners at 12 sites for one subject was measured in this study. Four contributing sources of variability were examined: (1) examiners, (2) trials, (3) systems, and (4) days.

Standard deviation was selected to quantify variability because it is the value most frequently used to estimate sample size, level of detectable difference and power for statistical analyses. Other measures of variability have been reported. For example, the coefficient of variation (CV), expressing standard deviation relative to the mean, can be useful in comparing distributions with different means [2]. However, as the mean approaches zero, as it frequently does for mean joint angles, CV increases rapidly and becomes meaningless. Also, the intraclass correlation coefficient [22,23], and the coefficient of multiple determination [4] have been used. Both of these rely on repeated measures for each examiner, which was not included in this study design. Additionally, these measures are dependent upon shape and range of the curve and cannot be easily compared across joint rotation curves.

The major finding of this study was that with no standardization protocol more than 75% of the overall variance could not be attributed to the motion capture systems, between days, or within sessions for most of the kinematic measures. This is most likely the result of variability between examiners due to differences in marker placement. Differences in how the examiners perceive the relationship between the technical coordinate system, defined by where markers are placed, and the underlying anatomic coordinate system that determines the calculation of joint angles, contribute greatly to between examiner variance. This is consistent with the work of Kadaba et al. [4], who identified marker placement errors as the primary source of between-session variability.

Within-session variability is not a major contributor to overall variance. Kadaba et al. [4] showed that the coefficient of multiple determination within session was high, especially in the sagittal plane. The variability of the subject walking within session is not impacted by marker placement differences. Between-session variability was higher than within-session variability, however this was still very low in magnitude compared to the overall variance. Between-session variability includes changes in the subject's walking patterns from day to day that are part of the inherent variability of the subject, as well as differences due to the examiner placing the markers in different locations. In the current study, between-session variability was measured at one site with

Table 4
The standard deviation (degrees) in the overall variability, variability due to the subject alone, and variability due to the system are shown for the first visit. The percent contribution of each component toward the total variance is shown in parentheses.

Parameter	Overall variability $N = 24$	Between-session $N = 6$	Between systems $N = 7$	Within-session $N = 24$
Pelvic tilt	3.5	1.5 (18%)	*	0.7 (4%)
Pelvic obliquity	1.2	0.2 (3%)	*	0.4 (8%)
Pelvic rotation	1.8	0.5 (8%)	*	0.9 (26%)
Hip flexion	24.8	1.0 (4%)	0.7 (2%)	1.0 (4%)
Hip abduction	5.0			0.5 (5%)
Hip rotation	7.3	1.1 (2%)	0.5 (0.5%)	0.7 (1%)
Knee flexion	4.8	0.7 (2%)	0.5 (1.1%)	0.8 (3%)
Ankle dorsiflexion	2.7	1.1 (17%)	0.2 (0.5%)	0.6 (5%)
Foot progression angle	2.6	0.9 (12%)	*	1.5 (33%)

*These variables are relative to the laboratory coordinate system and could not be evaluated by the test performed.

consistent marker placement to distinguish the variance due to the subject between days from the variance due to the examiner between days. It is possible that there were still some minor differences in alignment between days. The between-session variance was of the same magnitude as the within-session variance, suggesting that most of this variance was due to slight differences in the way the subject walked rather than to marker placement differences.

The motion capture systems themselves have some variability associated with determining marker locations. Based on these results, a properly configured and calibrated system contributes a negligible amount to the overall variability. It was expected and confirmed that the two commercial systems produce accurate and reliable 3D marker locations.

One source of variability not accounted for in this study design is that the subject could have walked differently at each site. This study took place over a several month interval at 12 sites across the United States. The effects of travel and time on the variability of kinematics were not controlled. Additionally, velocity has been shown to have an effect on gait kinematics [22,24]. The subject walked at a self-selected velocity and cadence, but did not walk with the same velocity at all sites. One alternative would have been to control cadence using a metronome as a means of controlling speed. It was felt that this would have created a less natural gait pattern that may have increased the between site variability.

Following development and implementation of a standardized gait analysis protocol, the study was repeated. Results were promising and showed an average 20% decrease in the standard deviation of 7 of 9 kinematic measures and an average 29% decrease in the maximum difference between examiners of 8 of 9 kinematic measures. Knee flexion and ankle dorsiflexion showed the greatest changes. This may be attributable to a focus in the training materials on identification of the knee flexion extension axis and reliable placement of the later femoral epicondyle marker. Foot progression angle showed a 15% decrease in standard deviation and a 31% decrease in range, which may be attributable to a focus on standardized identification of the long axis of the foot. In general, the results are promising and suggest that specific attention to marker alignment protocols may help to reduce the between examiner differences in kinematic measurement.

Care should be taken when generalizing the findings of this study to subjects with pathological gait. It is likely that differences will exist in the relative contributions of the sources of measurement error in subjects who have an abnormal gait pattern. For subjects with skeletal alignment abnormalities, marker placement may be more challenging and result in greater between examiner variability. Differences may also exist in the subject's variability in gait kinematics within and between sessions as a result of fatigue or underlying musculoskeletal or neurologic conditions.

The findings of this study point to the need for quality assurance measures and research that combine data collected from different motion analysis laboratories. The results suggest that laboratories should employ methods to reduce the variability in marker placement by examiners when involved in collaborative studies. Examiner training, the development of standardized protocols, and written descriptions of marker placement methodology may reduce examiner error. Modeling options that are not dependent on marker placement for calculating joint centers may be less variable. Longitudinal studies using different examiners, even within one site, should acknowledge measurement error as a potential contributor to observed differences. This has been recognized and promoted by Schwartz et al. [6], who have minimized between-session variability within one laboratory through improved quality assurance and training. Additionally, Tirosh and Baker [7] have recently described one method for quantifying and documenting between examiner variability.

This report documents sources and magnitudes of variability among 12 motion analysis laboratories. Marker placement differences between examiners are shown to be the most likely source of between site variability. Caution should be used when combining data from multiple sites without a standardized protocol and training program in place. Current efforts should be aimed at developing training programs to promote a uniform method of performing gait assessments to reduce measurement error between examiners.

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Conflict of interest

The authors had no conflict of interest when performing the study or when preparing the manuscript.

References

[1] Davis RB, Gorton GE, Aiona M, Scarborough N, Oeffinger D, Bagley A. A minimum standardized gait analysis protocol: development and implementation by the Shriners Motion Analysis Laboratory Network (SMALnet). In: Harris G, Smith P, editors. Pediatric gait - A new millennium in clinical care and motion analysis technology. Piscataway, NJ: IEEE Press; 2000. p. 1–7.
[2] Portney L, Watkins M. Foundations of clinical research: applications to practice, 2nd Edition, Upper Saddle River, NJ: Prentice Hall Health; 2000.
[3] Strube M, Delitto A. Reliability and measurement theory. In: Craik R, Oatis C, editors. Gait analysis: theory and application. St. Louis: Mosby; 1995.
[4] Kadaba MP, Ramakrishnan HK, Wootten ME, Gainey J, Gorton G, Cochran GV. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. J Orthop Res 1989;7(6):849–60.
[5] Chambers C, Goode B. Variability in gait measurements across multiple sites. Gait Posture 1996;4(2):167.
[6] Schwartz MH, Trost JP, Wervey RA. Measurement and management of errors in quantitative gait data. Gait Posture 2004;20(2):196–203.
[7] Tirosh O, Baker R. GAITABASE: a web accessible database for gait analysis. Springfield, MA: Gait and Clinical Movement Analysis Society; 2007.
[8] Skaggs DL, Rethlefsen SA, Kay RM, Dennis SW, Reynolds RA, Tolo VT. Variability in gait analysis interpretation. J Pediatr Orthop 2000;20(6):759–64.
[9] Noonan KJ, Halliday S, Browne R, O'Brien S, Kayes K, Feinberg J. Interobserver variability of gait analysis in patients with cerebral palsy. J Pediatr Orthop 2003;23(3):279–87. discussion 288–91.
[10] Kleissen R, Litgens M, Baten C, Harlaar J, Hof A, Zilvold G. Consistency of surface EMG patterns obtained during gait from three laboratories using standardised measurement technique. Gait Posture 1997;6(3):200–9.
[11] Armstrong AD, MacDermid JC, Chinchalkar S, Stevens RS, King GJ. Reliability of range-of-motion measurement in the elbow and forearm. J Shoulder Elbow Surg 1998;7(6):573–80.
[12] Brosseau L, Tousignant M, Budd J, Chartier N, Duciaume L, Plamondon S, et al. Intratester and intertester reliability and criterion validity of the parallelogram and universal goniometers for active knee flexion in healthy subjects. Physiother Res Int 1997;2(3):150–66.
[13] Somers DL, Hanson JA, Kedzierski CM, Nestor KL, Quinlivan KY. The influence of experience on the reliability of goniometric and visual measurement of forefoot position. J Orthop Sports Phys Ther 1997;25(3):192–202.
[14] Rome K, Cowieson F. A reliability study of the universal goniometer, fluid goniometer, and electrogoniometer for the measurement of ankle dorsiflexion. Foot Ankle Int 1996;17(1):28–32.
[15] Watkins MA, Riddle DL, Lamb RL, Personius WJ. Reliability of goniometric measurements and visual estimates of knee range of motion obtained in a clinical setting. Phys Ther 1991;71(2):90–6. discussion 96–7.

[16] Rheault W, Miller M, Nothnagel P, Straessle J, Urban D. Intertester reliability and concurrent validity of fluid-based and universal goniometers for active knee flexion. Phys Ther 1988;68(11):1676–8.
[17] Gogia PP, Braatz JH, Rose SJ, Norton BJ. Reliability and validity of goniometric measurements at the knee. Phys Ther 1987;67(2):192–5.
[18] Ekstrand J, Wiktorsson M, Oberg B, Gillquist J. Lower extremity goniometric measurements: a study to determine their reliability. Arch Phys Med Rehabil 1982;63(4):171–5.
[19] McDowell BC, Hewitt V, Nurse A, Weston T, Baker R. The variability of goniometric measurements in ambulatory children with spastic cerebral palsy. Gait Posture 2000;12(2):114–21.
[20] Sutherland DH, Olshen R, Cooper L, Woo SL. The development of mature gait. J Bone Joint Surg Am 1980;62(3):336–53.
[21] Growney E, Melgan D, Johnson M, Cahalan T, An KN. Repeated measures of adult normal walking using a video tracking system. Gait Posture 1997;6(2):147–62.
[22] [No author listed]. Effect of compensation procedures for velocity on repeatability and variability of gait parameters in normal subjects. Clin Rehabil 2006; 20(3):239–45.
[23] Monaghan K, Delahunt E, Caulfield B. Increasing the number of gait trial recordings maximises intra-rater reliability of the CODA motion analysis system. Gait Posture 2007;25(2):303–15.
[24] Jordan K, Challis JH, Newell KM. Walking speed influences on gait cycle variability. Gait Posture 2007;26(1):128–34.