THE DEVELOPMENT OF A NORMATIVE GAIT DATABASE

Chester, V. L., Tingley, M., and Biden, E. N.
Institute of Biomedical Engineering
University of New Brunswick, Fredericton, New Brunswick

ABSTRACT

Normative data is an essential component of clinical gait analyses. The Institute of Biomedical Engineering (IBME) at the University of New Brunswick has recently collected gait data from 58 normal children aged 1-13 years to establish a normative database. A six-camera Vicon 512 motion analysis system and force plates were employed to obtain temporal-spatial, kinematic, and kinetic parameters during walking. Statistical techniques, which allow quantitative comparison between this normative data and historical data from the Children's Hospital, San Diego, were used to assess normality of the new database. Significant differences between the 2 databases were found for sagittal joint angle data. It was concluded that data processing techniques and instrumentation are associated with these differences.

INTRODUCTION

Walking is the result of the complex interaction of active and passive forces acting about the joints of the body. The underlying biomechanics and neurophysiological mechanisms that facilitate walking are often not appreciated until they are impaired due to disease or injury. The loss or alteration of a person's walking skills greatly affects their ability to function and their quality of life. Clinical gait analysis aims to objectively quantify and assess the mechanics of walking. These analyses are critical to our understanding of normal and abnormal gait and treatment effectiveness.

A critical component of gait analysis is the availability of normative databases to compare patient data. One of the main objectives of gait analysis is to identify deviations in a patient's gait from 'normal' movement patterns. The underlying causes of these abnormal movement patterns are then identified and treatment recommendations are formulated (Davis, 1997). A children's gait database that is commonly used for such analyses was developed at the Children's Hospital, San Diego (Sutherland et al., 1988). The database contains joint angle data for 348 gait cycles for children aged 1.0 to 7.0 years old. However, it is often difficult to compare data across labs due to differences in marker sets, data processing techniques, and reliability of the clinician. As a result, caution must be exercised when comparing patient data to normative results obtained from other labs. Further difficulty in comparing patient data to normative data sets is due to advances in computer technology which have dramatically improved motion analysis systems and data processing capability over the last decade. For example, San Diego used a manual digitization motion analysis system and represented most angles as planar projections. Currently, three-dimensional analyses of gait using more sophisticated motion capture and data analysis techniques are commonplace in gait clinics.

Given the important role of normative data in gait analyses and the difficulties associated with comparing data across labs, the objective of this study was to develop a normative database for the Institute of Biomedical Engineering (IBME) at the University of New Brunswick. In doing so, patient data can be compared to normative data obtained by the same clinician, equipment, marker systems, and data processing techniques. As a result, more reliable comparisons of data sets can be achieved. The normative sagittal data was compared to historical data from the Children's Hospital in San Diego. In addition, statistical classifiers were used to assess the normality of the new database.

METHOD

Subjects

Fifty-eight children aged 1-13 years old were recruited from the Fredericton area by distributing research bulletins around the University of New Brunswick campus and local daycare centres. Parental consent was obtained prior to each child's participation in the study. Parents voluntarily completed a questionnaire designed to identify possible injuries or diseases that could affect their child's walking skills. No children were eliminated from the study based on these responses.

Instrumentation/Apparatus

A Vicon 512 motion capture system (Oxford Metrics Ltd.) was employed to track the three-dimensional trajectories of reflective markers placed on the subjects' skin at a sampling frequency of 60 Hz. In addition, two force plates (Kistler 9281B21 and AMTI BP5918), collected the three-dimensional ground reaction forces and moments during each gait cycle. The plates were embedded at the center of a

6.7 X 0.9 meter wooden walkway. The walkway was of sufficient length to allow each child to attain steady state velocity through the recording area. Two digital cameras, a weight scale, and calipers were used to obtain anthropometric measures from each subject.

Procedures

All data collection was conducted at the motion analysis laboratory at the University of New Brunswick. Twenty-one reflective markers, representing key anatomical landmarks, were placed on the skin of each subject (skin marker locations: left and right heel, lateral malleolus, 2nd metatarsal, lateral epicondyle, greater trochanter, asis, shoulder; sacrum and C7). To ensure accurate placement of markers, participants were asked to wear minimal clothing or bathing suits during data collection. Participants were placed at specific locations at the beginning of the walkway to ensure accurate foot strikes on the force plates during the gait cycle. Each child was encouraged to pay attention to objects (e.g. toys) placed at the end of the walkway to avoid targeting of the force plates. Several 'warm-up' trials were conducted to allow the participants to adjust to the markers and the walkway. Immediately following completion of the gait trials, the reflective markers were removed and a new segment inertia marker set (Jensen, 1978) was applied. Participants were then asked to stand in the anatomical position within a calibration frame, while simultaneous front and side digital photographs were taken. Anthropometric data such as joint width, height and mass were then measured.

Data Analysis

A comprehensive kinematic and kinetic analysis of each child's gait was performed. The criteria for selection of gait trials for each child were based on the following: 1) parental acknowledgment of a 'normal' gait cycle for their child and 2) successful force plate strikes during the trial. From the selected trials, cadence, velocity, and percent of cycle spent in single stance were calculated for each gait cycle. The single gait cycle, which most closely approximated the mean of all gait cycles on these three measures, was selected as the final trial for analysis. Joint angles were then processed using two different methods: 1) Euler angles, and 2) projected angles.

Euler Method

The body was modeled as a series of rigid links joined by 3 degree of freedom articulations. The model consisted of the left and right foot, shank, thigh and the pelvis and trunk. Joint center locations were estimated in accordance with Davis et al., (1991). Temporal-spatial measures and joint angles were calculated from the three-dimensional coordinates produced by the Vicon motion analysis system. The three non-collinear markers on each body segment were used to create embedded coordinate systems at the joint centers. Joint angles were computed from the relative orientations of the embedded coordinate systems using Euler angles in a *yxz* sequence, corresponding to flexion/extension, adduction/abduction, and internal/external rotation. The joint angle curves were approximated by a finite Fourier series using 6 harmonics.

To calculate joint moments and power during walking, the inertial properties of the segments are required. A mathematical model (elliptical cylinder method) of the human body was used to estimate the segment inertial properties of each child (Jensen, 1978). This technique requires the digitization of the full body images obtained from the digital photographs of each participant in the anatomical position. The model consists of 16 segments and each segment is assumed to consist of elliptical cylinders created at 1 cm intervals in the transverse plane. Given that the volume and density of each elliptical cylinder is known, the mass of each elliptical cylinder is calculated. The segment mass, center of mass location, and moments of inertia are then calculated from the stacked elliptical cylinders representing each segment.

Net joint moments and joint power for the hip, knee, and ankle joints were estimated using the inverse dynamics approach. This technique combines the motion data, force plate data and segment inertial data. The required absolute linear and angular velocities and accelerations were calculated from the embedded coordinate systems using a five-point derivative. These data were filtered using a 6 Hz low-pass Butterworth filter. Frictional torque, center of pressure, and ground reaction forces were computed from the force plate data. The data was then smoothed using a 21 pt Hann moving window average.

San Diego Projection Angle Method

Joint angle data were also computed for the normative group using the projection angle algorithms used by Sutherland et al., (1988). Similar to Sutherland et al., the joint angle curves were approximated by a finite Fourier series using 6 harmonics.

Statistical Analysis

Despite the vast amounts of data computed for the normative database, only the sagittal hip, knee, and ankle kinematics were analysed statistically to assess the normality of the data. This was for 2 reasons: 1) only kinematic data was readily available for comparison from the San Diego Children's Hospital, and 2) sagittal hip, knee, and ankle joint angles tend to demonstrate greater consistency across labs than smaller rotations in other planes (Biden et al., 1987). Therefore, more reliable comparisons were possible using this reduced data set.

The statistical analysis was based on a one-dimensional index of normal gait developed by Tingley et al., (2002). Given that the amplitude of joint angle data is sensitive to marker positioning error, each child's angular displacement curve was recentered by subtracting its mean, prior to analysis. To calculate the index of normal gait, Tingley et al. calculated eleven interpretable functions from the San Diego normative data. These functions represent the mean sagittal joint angle patterns for hip, knee and ankle (3 functions), the mean angular velocities of the three joints (3 more functions), the angular acceleration patterns of the three joints (3 functions), and two functions which capture the primary frequencies of knee and ankle angle patterns. A key finding in Tingley's study was that each child's pattern of variation from the group mean could be approximated as a linear combination of these interpretable functions. The gait index developed in this work is simply a squared distance calculated in 11 dimensions (Mahalanobis distance). The gait index classifies children as normal, abnormal, or unusual based on calculations of population percentiles.

We used the interpretable functions and covariance matrix supplied by Tingley et al to calculate index scores for the 71 left and right gait cycles collected at UNB for children aged 3-13 yrs. Children under the age of 3.0 years were omitted from this training, as their gait patterns were immature (i.e. would be classified as abnormal). The analysis classified children's gait patterns based on their deviation from San Diego mean normative values. The statistical classifier was then 'recalibrated' using the IBME normative data. New values for the interpretable functions and a new covariance matrix (required for the distance calculation) were computed. New index scores were calculated for the IBME data and the two sets of classification results were compared. The ability of the recalibrated index to detect abnormal gait patterns was tested by computing the index for children under the age of 3 years. A further examination of the differences between the San Diego and IBME normative data sets was conducted using a multivariate analogue of the two sample t-test of the joint angle data (Seber, 1984). These tests compared differences between the San Diego data and IBME's Euler angle data, and San Diego and IBME projected angle data.

RESULTS

The classification of IBME's kinematic data for children aged 3-13 years, based on San Diego mean normative values, resulted in 49% of cycles being classified as unusual or abnormal. However, when the statistical classifier was recalibrated using the IBME normative data, the new index gave results similar to those of Tingley et al: the score behaved like an $F_{11,61}$ statistic for the training data, classifying 94% of cycles as normal. Further testing using the gait patterns of younger children showed that the classifier was also capable of detecting 80% of immature (i.e. abnormal) gait patterns.

The differences between the two gait index calculations were readily explained by appropriate statistical tests: the first test compared the covariance structure of sagittal angle displacement curves from each lab, while the second test compared mean angle patterns from each lab. Both tests yielded highly significant P-values (p=0.000). Figure 1 shows the IBME mean hip, knee and ankle joint angle curves (± 2 S.E.) with the San Diego mean normative data superimposed. Although the graphs appear similar at first glance, the two databases are quite distinct. For example, the peak mean knee flexion between the two databases is more than 2 standard errors apart. When IBME angles were recalculated, using a projected angle approach similar to that used at San Diego, mean angle patterns were slightly closer to those of San Diego, but still significantly different (p=0.000). Figure 2 shows the mean results for knee flexion for San Diego's data, IBME's Euler data, and IBME's projected angle data. IBME projected angles are more similar to San Diego's data at the beginning and the middle of the gait cycle.

DISCUSSION

It is generally accepted that comparisons of data from multiple labs should be conducted with caution. It is possible that a patient's gait data could be incorrectly diagnosed as abnormal using normative data from other labs. The results of this study suggest that databases developed using different technological and computational methods will show different normative values. These differences were evident in gait variables that are generally considered to be consistent across gait labs. The significant differences found between the San Diego and IBME

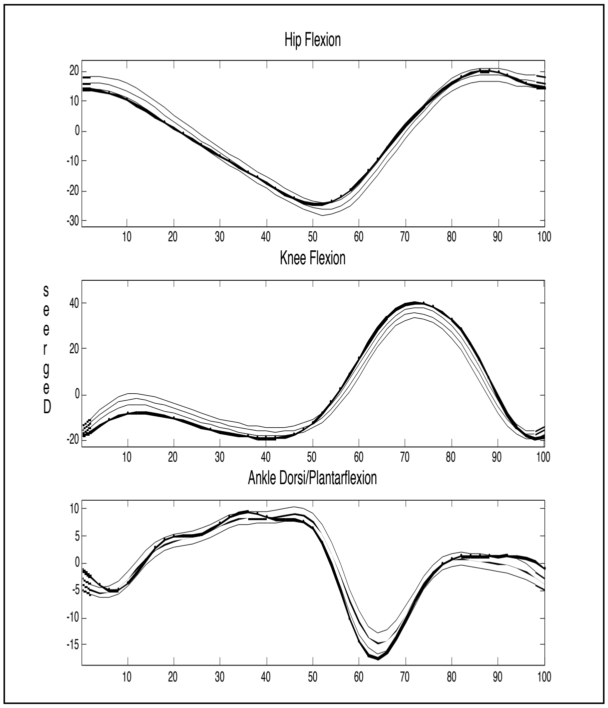

Figure 1. Mean ± (2 S.E.) hip, knee, and ankle joint angles for IBME normative data (thin lines) with San Diego mean data superimposed (thick lines).

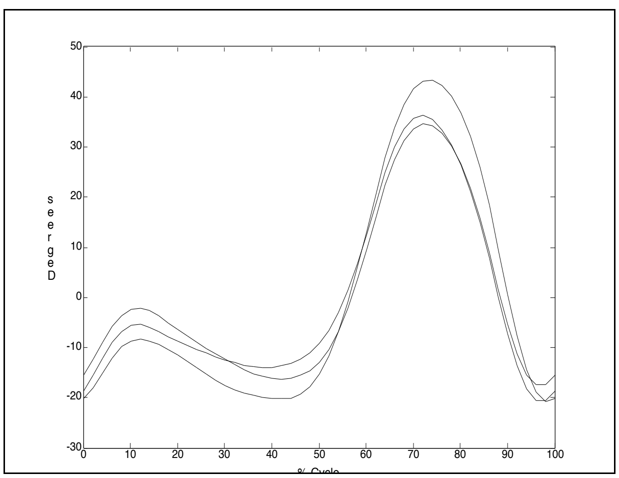

Figure 2. Mean results for knee flexion angles using IBME's euler (_) and projected angle data (---) and San Diego projected angle data (_ -).

normative databases are likely due to a combination of factors. The results of the multivariate analyses show that the data differ in part due to the algorithms used to calculate the joint angles. IBME's normative data showed more similarity to the San Diego values when joint angles were calculated as projected angles instead of Euler angles. This is expected as Sutherland et al., (1988) also used projected angles to compute their data. The databases may also vary because of other differences in data processing techniques such as the number of samples used to compute the joint angles and methods used to identify joint center locations. Differences in the motion analysis systems used to collect the databases could also be a factor. Sutherland et al. used a pseudo three-dimensional, manual digitization system. In contrast, IBME uses a three-dimensional, semi-automatic digitization system. Therefore, efforts to develop normative databases using more current techniques are needed.

The results of the one-dimensional index of normality suggest that the retrained classifier should be used for future gait analyses at IBME when Euler angles are used. An interesting finding was that the recalibrated index of normality identified 80% of cycles for children under 3 years old as unusual or abnormal. This supports the findings of Tingley et al. that the eleven interpretable functions can successfully classify gait patterns.

CONCLUSION

Gait analyses using three-dimensional Euler angles should refer to normative data developed using the same algorithms. In addition, statistical classifiers of gait normality should be recalibrated on more recent databases. Efforts to develop new and large normative databases with modern equipment and processing techniques are warranted. Normative data from this study is available at **www.math.unb.ca/~maureen/gait.**

REFERENCES

Biden, E.N., Olshen, R.A., Sutherland, D.H., Gage, J., & Kadaba, M. (1987). Comparison of gait data from multiple labs. *Transactions of the Orthopaedic Research Society, January.*

Davis, R. B. (1997). Reflections on clinical gait analysis. *Journal of Electromyography and Kinesiology, 7 (4)*, p. 251-257.

Jensen, R. K. (1978). Estimation of the biomechanical properties of three body types using a photogrammetric method. *Journal of Biomechanics, 11*, 349-358.

Seber, G. (1984). Multivariate Observations. New York: John Wiley & Sons.

Sutherland, D.H., Olshen, R.A., Biden, E.N., & Wyatt, M.P. (1988). The Development of Mature Walking. London: MacKeith Press.

Tingley, M., Wilson, C., Biden, & Knight, W. (2002). An index to quantify normality of gait in young children. *Gait and Posture, (In Press).*