A polynomial function of gait performance

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Summary

A mathematical data processing method is presented that represents a further step in gait analysis. The proposed polynomial regression analysis is reliable in assessing differences in the same patient and even on the same day. The program also calculates the confidence interval of the whole curve. The procedure was applied to normal subjects in order to collect normative data. When a new subject is tested, the polynomial function obtained is graphically superimposed on control data. Should the new curve fall within the limits described by normative data, it is considered to be equivalent. The procedure can be applied to the same subject, either normal or pathological, for retesting kinematic characteristics. The gait cycle is analyzed as a whole, not point-by-point. Ten normal subjects and two patients, one with recent- and the other with late-onset hemiplegia, were tested. Multiple baseline evaluation is recommended before the start of a rehabilitation program.

KEY WORDS: gait, hemiplegia, rehabilitation.

Introduction

Video recording is the most widely used method in clinical settings for the evaluation of posture and motion, which involve several joints simultaneously. Several limitations are acknowledged, such as the qualitative nature of the assessment, the problem of inter-observer variance, and the fact that the motion analysis is only two-dimensional. These limitations prompted the development of electronic gait analysis (GA), a technique that is able to supply the clinician with quantitative, three-dimensional information relating both to kinematic and dynamic aspects of motion and to the pattern of muscle activation during a given motion (1).

Gait analysis is a useful routine intervention in the rehabilitation field (2). Yet, questions have arisen about the implications of intra-individual variance in patients with neurological diseases, when rehabilitation is called for. When the gait pattern is stabilized, rehabilitation treatments are no longer effective (3), however, even stabilized gait patterns can change (e.g., when botulin injections are administered). GA can provide data on possible functional improvements obtained as a result of external intervention.

The aim of the present research was to find a rapid method of comparing separate recordings of gait parameters obtained from the same person during a rehabilitation program. For this purpose, we applied non linear regression methods to the experimental curves, obtained by means of gait recordings, in order to determine:

– the regression functions that approximate the averaged curve of the gait performances of healthy volunteers;
– the regression functions that may describe the gait of patients suffering from post-stroke hemiplegia.

The present methodology can be applied in GA laboratories for rehabilitation purposes. The creation of clear graphs and clear tables, as the output of a polynomial regression analysis, is useful from the perspective of evidence-based medicine.

A clinical audit is a systematic analysis of the quality of health care, and accreditation standards for rehabilitation centers are increasingly demanding quantitative evaluations and intra-individual comparisons. This is a necessary development as the rehabilitation field is chronically plagued by ordinal scales. For example, spasticity is usually measured using the five-point Modified Ashworth Scale (which goes from “No increase in muscle tone” to “Affected part rigid”) on the basis of a subjective evaluation of the stretch reflex. This means that once patients are discharged they can no longer be evaluated within the framework of a clinical audit. By contrast, the quality of health care can be improved through regularly performed and properly documented clinical audits based on clear and objective and measurements that can be reviewed, even when the patient is no longer under treatment.

Material and methods

Ten healthy volunteers (mean age 58.2±5.5 years) were invited to the GA Laboratory of the Rehabilitation Center and asked to walk. Flexion and extension of the hip, knee and ankle were considered. Their performances were compared with those of two patients presenting...
with post-stroke hemiplegia. The first one (male, 66 years old) had suffered a stroke one year before and appeared to be stabilized. The second patient (male, 61 years old) was a more recent case, having suffered a stroke three months earlier. The patients could walk with aids but the recording session was undertaken without any aids, since only a few steps were required. The complete evaluation consisted of three components: clinical examination, videotaping and three-dimensional GA. In particular, for the 3D gait analysis, we used a 12-camera optoelectronic system with passive markers (ELITE 2002, BTS, Italy) working at a sampling rate of 100 Hz to measure the kinematics of movement. The markers were positioned as described by Davis (4). The subjects were asked to walk barefoot at their own natural pace (self-selected speed) along a 10-meter walkway. Two trials were collected for each subject on the same day in order to check the repeatability of the results. Kinematic data reduction was based on Euler angles and Euler’s equations of motion. The gait cycle was subdivided into 100 points separated by equal intervals. ASCII data from the instrument were inserted into a computer where a “best fit” analysis was performed using the MatLab 7.1 Curve Fitting Toolbox (The Math Works Inc., Natick, MA, USA). Once the option “polynomial regression” (5) had been selected, the best approximating polynomial function was determined, by taking into account the $R^2_{adj}$ term (degree of freedom adjusted coefficient of determination). The prediction bounds of the regression line were also calculated. These confidence limits were simultaneous. In other words, they were referred to the estimated curve for all the X values, considered at the same time. To obtain a reference pattern, we considered the averaged recordings of gait in normal controls as well as the averaged recordings of gait in the same patient at baseline.

The study was approved by the local internal review board. The subjects gave their written consent to participate.

Results

When flexion and extension were considered, the best fit (the continuous line in the figures) was expressed by a 9th degree polynomial function:

$$y(x) = p_0 + \sum_{k=1}^{9} p_k x^k$$

in which y and x indicate the measured angle and the step of the gait cycle, respectively. The hip, knee and ankle could be analyzed separately. In the normal subjects the approximation was high. Indeed, we always found: $R^2_{adj}>0.9$. A value equal to 1 would mean perfect correspondence between experimental and estimated values. Dashed and dotted lines indicate the prediction bounds of the regression curves (Fig. 1).

The ankle motion system appeared to be more complex. Although the 9th degree regression polynomial was close to 1 ($R^2_{adj}=0.945$), local discrepancies were found and the area within the confidence limits was wider than that seen for the hip and knee. The discrepancies were more evident around the minimal point of the curve, representing the most negative point of the flexion-extension angle. If the curve was divided into two halves, a better approximation could be obtained. However, this issue is beyond the scope of our analysis.

Two left hemisphere injured patients were also studied. The gait of both patients was analyzed twice on the same day (Fig. s 2 and 3). The first recording was taken as the reference pattern. The procedure allowed us to identify at a glance the gait phases in which local differences were produced. In fact, if both the experimental values and estimated values (by means of the polynomial approximation) were embedded at retest in the ribbon on the graph of confidence limits, stability of kinematic parameters could be inferred.

On re-testing, the first patient had, during the intermediate phase of the gait cycle (from 0.25 to 1 on the X-axis), hip and knee flexion-extension data that were outside the confidence limits obtained in the first test session. When ankle motion was considered, the retest curve was inside the confidence limits of the reference pattern indicating that the kinematics of ankle motion were globally stable. However, higher maximal angles were observed in the second session. The angle was also slightly delayed if compared to the highest value of the first curve.

The second patient had suffered a more recent stroke and showed unstable gait patterns. In fact, at retest both the experimental and the fitted curves were outside the confidence limits of the reference pattern. For the sake of brevity, only the plots referring to knee joint are shown here.

![Figure 1 - Knee flexion and extension: 95% simultaneous bounds for observation in control group. Squares: experimental data. Solid line: fitted curve. Dashed-dotted lines: prediction bounds. Y-axis: degrees of motion. X-axis: normalized data of 100 gait cycle measurements. $R^2_{adj}=0.996$](image)

Discussion

An observed gait cycle was compared with a reference pattern in order to identify the phases of the gait cycle in which the new curve is outside the confidence limits. Indeed, the capacity to make a precise judgment on sta-
bility or changes yielded by treatment is a critical issue in rehabilitation. The polynomial degree and the coefficient values can provide an answer. Indeed, curves will differ significantly from one another if either the regression polynomial degree or coefficient values change, in the case of optimal regression polynomials having the same degree.

A procedure for obtaining a simple graphic representation is the following. The best regression polynomial is calculated and measured points are plotted with the best fitting model and the simultaneous confidence limits. If stability exists, the data obtained at retest should remain within the ribbon designed on the graph by the confidence limits.

Other mathematical models of human gait are based on fractal analysis and consider only step length (6). Our approach, connected to the design of GA, takes into consideration the angles of joint motion and is aimed at investigating the kinematics of human walking. The results indicate that it is possible to evaluate changes in gait patterns in subsequent trials. The simultaneous confidence limits which were calculated at retest should remain within the ribbon designed on the graph by the confidence limits.

Table I - Values of knee motion in normal subjects, \( R^2_{adj}=0.996 \).

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Confidence interval at 95%</th>
</tr>
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<tbody>
<tr>
<td>( p_0 = 14.31 )</td>
<td>([13.76, 14.86])</td>
</tr>
<tr>
<td>( p_1 = 60.17 )</td>
<td>([58.14, 62.2])</td>
</tr>
<tr>
<td>( p_2 = 85.26 )</td>
<td>([81.61, 88.91])</td>
</tr>
<tr>
<td>( p_3 = 31.06 )</td>
<td>([24.32, 31.88])</td>
</tr>
<tr>
<td>( p_4 = -177.1 )</td>
<td>([-123.1, -111.2])</td>
</tr>
<tr>
<td>( p_5 = -33.81 )</td>
<td>([-43.24, -24.38])</td>
</tr>
<tr>
<td>( p_6 = 52.48 )</td>
<td>([49.13, 55.83])</td>
</tr>
<tr>
<td>( p_7 = 25.01 )</td>
<td>([20.06, 29.43])</td>
</tr>
<tr>
<td>( p_8 = -7.695 )</td>
<td>([-8.296, -7.095])</td>
</tr>
<tr>
<td>( p_9 = -4.181 )</td>
<td>([-4.88, -3.483])</td>
</tr>
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Finally, our data obtained from polynomial regression analysis, indicate that ankle motion is the component of gait showing the highest variance after stroke. Conversely, peak hip extension was the only gait parameter found to be lower in normal elderly subjects compared to young adults (8); an elderly population was also found to show less certainty of the neuromuscular system of the knee and hip in selecting a stable range of motion during gait (9). GA thus confirms that aging and stroke have quite different influences on the muscular system of the ankle. A limitation of this study is the lack of a single p value for rejecting the null hypothesis, i.e., no variation when several gait curves during the rehabilitation treatment are compared. This is due to the multivariate nature of the analysis that considers the whole gait cycle. Therefore, clinicians have to base their inference on simultaneous confidence limits. Joint abduction-adduction and extra-intra rotation require further studies. The ability to detect
abnormalities in patients (e.g. after stroke) needs to be
confirmed in a large number of patients. The present ar-
ticle is a technical note, indicating a new way of plotting
data for inclusion in the patient’s file.

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