High curvature and jerk analyses of arm ataxia

Dov Goldvasser¹, Chris A. McGibbon¹,²,³, David E. Krebs¹,²,³

¹ Massachusetts General Hospital, Biomotion Laboratory, Boston, MA 02114, USA
² MGH Institute of Health Professions, Boston, Mass., USA
³ Harvard Medical School Department of Orthopedics, Boston, Mass., USA

Received: 17 December 1999 / Accepted in revised form: 7 July 2000

Abstract. We investigated high curvature analysis (HCA) and integrated absolute jerk (IAJ) for differentiating healthy and cerebellopathy (CB) patients performing pointing tasks. Seventeen CB patients and seventeen healthy controls were required to move a pointer at their preferred pace between two 50.8 cm laterally spaced targets while standing with their arm extended in front of their body. HCA was used to quantify the frequency of sharp turns in the horizontal-plane (anterior-posterior and medio-lateral) velocity trajectory of the hand-held pointer. IAJ was assessed by integration of absolute jerk (second time derivative of velocity) time histories in the anterior-posterior and medio-lateral directions. HCA scores and IAJ scores were then compared between CB patients and healthy controls; for both analyses, higher scores indicate less smooth movements. We hypothesized that CB patients would have less smooth movement trajectories than healthy controls due to upper extremity ataxia associated with cerebellar disease and degeneration. We found that CB patients had higher HCA scores than healthy controls (P = 0.014). Although CB patients had higher IAJ scores in both anterior-posterior (P = 0.060) and medio-lateral (P = 0.231) directions compared to the healthy controls, the differences were not significant. The difference in sensitivity between the HCA and the IAJ analysis might be explained by primitive neural activation commands, ubiquitous though only evident with some cerebellar dysfunctions, which produce submovements which are themselves minimal jerk curves. We conclude that HCA may be a useful tool for quantifying upper extremity ataxia in CB patients performing a repeated pointing task.

1 Introduction

Clinicians often use rapid alternating movements, or dysmetria tests, for quantifying cerebellar ataxia (Jankovic and Tolosa 1988; Notermans et al. 1994). However, assessing performance in the clinic during standard dysmetria tests, such as the finger-to-nose test, is in general more qualitative than quantitative. Although advantageous from a clinical perspective, the sensitivity of these tests has been questioned (Notermans et al. 1994; Sullivan et al. 1991; Swaine and Sullivan, 1992, 1993). Alternatively, conducting dysmetria tests in a motion analysis laboratory enables objective and accurate quantification of the smoothness of movement, allowing more complex movements, and their submovements, to be analyzed in great detail (Flash and Hogan 1985; Hogan et al. 1987; Kaminski and Gentile 1989; Nagasaki 1989; Schneider and Zernicke 1989; Suzuki et al. 1996; Gielen et al. 1997; Topka et al. 1998a,b; Krebs et al. 1999).

Krebs et al. (1999) investigated arm movement smoothness in the horizontal plane of patients with brain injury following cerebral vascular accident. Their study presented a plausible hypothesis that movement trajectories of the arm during a point-to-point task consist of multiple smooth sub-movements that blend into an overall smooth trajectory. Patients with stroke injury demonstrated these sub-movements but not the ability to blend those movements (Krebs et al. 1999). Geilen et al. (1997) and Kaminski and Gentile (1989) observed that arm trajectories in healthy subjects trace a two-dimensional curved surface, thus reducing the degrees of freedom required for control of movements. Bastian et al. (1996) studied arm movements in patients with cerebellar pathology (CB) and healthy controls during a reaching task. CB patients demonstrated abnormally curved wrist trajectories, further characterized by undershoot (during slow movements) and overshoot (during fast movements) of the target, compared to the healthy controls. Observation of joint torques during the tests suggested a major role of the cerebellum is the regulation of interaction torques to control multi-joint movements (Bastian et al. 1996).
As suggested by Gielen et al. (1997), the characteristic pattern of cerebellar ataxia – jerky and segmented movements – is contained in the trajectory of the hand during repeated arm movements. We present a technique called high curvature analysis (HCA) for quantifying the velocity trajectory smoothness of a single point in space (the hand or pointer) during the repeated, cyclic arm movements of a point-to-point test. We hypothesize that the frequency of high curvature transitions in the velocity trajectory, due possibly to segmented movements, will successfully discriminate between CB patients and healthy controls. We also compare the HCA analysis to integrated absolute jerk (IAJ) analysis in order to gauge the sensitivity of the HCA technique.

2 Methods

2.1 Subjects

Seventeen healthy subjects with average age 38.2 ± 16.6 (mean ± SD) years and seventeen subjects with cerebellar pathology having average age 47.7 ± 11.4 years were included in these tests. Healthy subjects were free of musculoskeletal disorders, visual impairment (or were corrected for visual impairment), and vestibular or central nervous system disorders. The CB patients were diagnosed by a neurologist using MRI or CT scans to demonstrate cerebellar deficiency, and they showed symptoms of locomotor and balance impairment upon clinical examination (Gill-Body et al. 1997). Apart from their CB dysfunction, the patients were healthy (no significant co-morbidity) and were able to rise from a chair and walk unassisted. All subjects provided informed consent in accordance with institutional policy on human research.

2.2 Instrumentation

Data were collected using a SELSPOT II optoelectric system (Selective Electronics, Partille, Sweden). Motion data were sampled at 150 Hz from 11 body segments: feet, shanks, thighs, pelvis, thorax, upper arms, and head. An array of infrared light-emitting diodes were attached to each of these body segments. For pointing trials, an additional pointer array was held by the subject’s dominant hand. The three-dimensional position and rotation in space of the center of each segment array was calculated by using TRACK software (Massachusetts Institute of Technology, Cambridge, Mass.). For the purpose of this investigation we analyzed only the movement data from the hand-held pointer.

2.3 Protocol

Subjects were positioned in the center of the camera’s viewing volume in front of and at arm’s length from a T-shaped structure (Fig. 1a). The structure was positioned such that the subject’s arm intersected the center of the structure in the neutral position. The height of the target apparatus was set at each subject’s umbilical height. Subjects were instructed to move the pointer repeatedly from one marker to the other at a self-selected speed (Fig. 1b) using their shoulder with elbow and wrist locked. Data were collected for a period of ten seconds and each subject repeated the experiment twice. Data collection began once the motion reached a steady state, which generally occurred after one or two pointing cycles.

2.4 Data analysis

2.4.1 High curvature analysis. High curvature analysis is a method used in image analysis to detect sharp corners, such as structure edges (for the complete method see Chetverikov and Szabo 1999). Essentially, lines within an image are scanned and the angle subtended by discrete triplets of points are successively determined using the cosine law from the first to the last element of the line. Briefly, a triangle was created by defining three points \( P_{i-1}, P_i, \) and \( P_{i+1} \) along the trajectory (Fig. 2). The angle \( \alpha \) subtended by the three points was calculated from

\[
\alpha = \cos^{-1}\left(\frac{AA + BB - CC}{2AB}\right)
\]
Fig. 2. High curvature analysis (HCA) calculation: the angle $\alpha$ between vector $A$ and vector $B$ is calculated based on the cosine law; if the angle is below $80^\circ$, the point is registered as a high curvature point. All high curvature points are then counted along the length of the trajectory.

where

\[ A = |P_{i-1} - P_i| \]
\[ B = |P_i - P_{i+1}| \]
\[ C = |P_{i-1} - P_{i+1}| \]

Points $P_{i+1}$ and $P_{i-1}$ were equally spaced from point $P_i$ by five data points (representing a time resolution of 33 ms). The high curvature angle, $\alpha$, was calculated for each point in the trajectory for $i = 2, 3, \ldots n - 1$ where $n$ is the total number of points in the vector. We chose a threshold of $80^\circ$; the middle point any set of three points with a subtended angle less than this threshold was considered a sharp curvature point. The frequency of high curvature angles within the horizontal-plane (anterior-posterior and medio-lateral) velocity trajectory of the hand pointer for CB and healthy control subjects were documented and normalized to the number of complete pointing cycles.

2.4.2 Integrated absolute jerk. Jerk was calculated from the third time derivative of pointer displacement. The absolute value of the jerk time history was then integrated over the duration of the pointing task (including the reversal phases of movement), and normalized to the number of complete pointing cycles. A problematic characteristic of successive time derivatives is the multiplicative effect upon the power of high frequency noise in the signal. Kinematic data were initially filtered at 6 Hz using a low-pass Butterworth fourth-order filter, and then filtered (using the same filter characteristic) between each successive time derivative. This additional treatment does not affect the frequency content, but rather attenuates the higher frequency harmonics in the signal; the pointing movement had a dominate frequency of approximately 1.5 Hz, and therefore the successive filtering scheme was unlikely to eliminate any critical information. The IAJ, or total area under the absolute jerk curve, per cycle was evaluated separately along the anterior-posterior and medio-lateral directions.

3 Results

Representative horizontal-plane velocity trajectories for three healthy controls and three CB patients are shown in Figs. 3 and 4, respectively. It is evident that the CB subjects have less smooth movements than the healthy

Fig. 3. Pointer velocity trajectories for typical healthy subjects
subjects. Tables 1 and 2 summarize the quantitative results for HCA and IAJ analyses. Note that because the HCA is performed directly on the trajectory (by definition, kinematics in a plane), only one number is required to characterize smoothness of movement. In contrast, jerk analysis is conducted on time histories (in order to perform the integrations) and therefore two numbers are generated; one in the anterior-posterior and one in medio-lateral directions. We found that regardless of the method used (HCA or IAJ) and the direction of motion (anterior-posterior or medio-lateral for IAJ analysis), the mean score was always lower for healthy subjects compared to CB patients.

Statistical analysis, however, indicated that the HCA approach was more sensitive to ataxic arm movements than the IAJ analysis. As illustrated in Fig. 5, healthy subjects had an average of 2.65 sharp curves per cycle while CB subjects averaged 5.30 sharp curves per cycle; this difference was significant ($P = 0.014$). The IAJ analysis reveals only a moderate difference along the anterior-posterior axis ($P = 0.060$) and no significant difference along the medio-lateral axis ($P = 0.231$).

### 4 Discussion

Although movement characteristics associated with cerebellar ataxia are well documented, the underlying mechanisms are unknown (Bastian 1996). The disorder is mainly characterized by irregular and hypermetric (overshoot) movement trajectories of the arm and hand during repeated pointing or reaching tasks (Bonnefoi-Kyriacou et al. 1995; Ramos et al. 1997; Topka et al. 1998a). This lack of movement coordination is thought to be due in part to difficulties in regulating muscle interaction torques (Bastian et al. 1996; Riener and

---

**Table 1.** High curvature analysis (HCA) and integrated absolute jerk (IAJ) results for healthy control subjects. ($A/P =$ Anterior-posterior, $M/L$ medio-lateral)

<table>
<thead>
<tr>
<th></th>
<th>HCA Score</th>
<th>IAJ-A/P</th>
<th>IAJ-M/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2.65</td>
<td>2200</td>
<td>4667</td>
</tr>
<tr>
<td>SD</td>
<td>$\pm$ 3.38</td>
<td>$\pm$ 1627</td>
<td>$\pm$ 2857</td>
</tr>
</tbody>
</table>

**Table 2.** Results for cerebellar dysfunction patients

<table>
<thead>
<tr>
<th></th>
<th>HCA Score</th>
<th>IAJ-A/P</th>
<th>IAJ-M/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>5.30</td>
<td>2854</td>
<td>5188</td>
</tr>
<tr>
<td>SD</td>
<td>$\pm$ 3.36</td>
<td>$\pm$ 1740</td>
<td>$\pm$ 2858</td>
</tr>
</tbody>
</table>

**Fig. 5.** HCA scores compared to integrated absolute jerk (IAJ) scores for healthy controls and cerebellar dysfunction (CB) patients. IAJ scores should be multiplied by a factor of 1000.
Straube 1997; Topka et al. 1998b). The latter explanation is certainly applicable to multi-joint movements where muscle and inertial interaction between two or more joints and segments is necessary to execute a task, and may also explain (perhaps to a lesser degree) the ataxia observed during quasi-single joint movements, as illustrated by the data presented here. Visual interaction also has an influence upon the degree of ataxia and can be responsible in part for uncoordinated single-joint movements (Gielen et al. 1997), as well as postural deficits that influence whole-body position control, hence arm control (Kaminski et al. 1995).

Methods of quantifying ataxia during arm movements have mainly involved using jerk as the measure of smoothness of movement (Flash and Hogan 1985; Nagasaki 1989, 1991; Schneider and Zernicke 1989; Latash et al. 1995; Suzuki et al. 1996; Krebs et al. 1999). Flash and Hogan (1985) modeled coordination using minimum-squared jerk as an objective function to define the optimal dynamic performance of two-joint arm movements. The model predicted near straight lines and bell-shaped velocity curves for point-to-point movements. Krebs et al. (1999) used this technique to analyze arm movements in patients with brain injury. Their study demonstrated that apparently continuous arm movements consist of sub-movements, each having a bell-shaped velocity curve satisfying the minimum jerk requirement (Krebs et al. 1999). Furthermore, the bell-shaped velocity curves were strikingly similar to the velocity curves observed for healthy subjects performing point-to-point movements, suggesting that a primitive unit action exists in producing these movements. Other studies have compared minimum jerk cost for arm movements at different speeds, concluding that jerk cost is minimal at intermediate speeds of movement (presumably in the range of one’s preferred velocity) but increases for slower and faster movements (Nagasaki 1989) and decreases with practiced movement (Schneider and Zernicke 1989).

Based on the above studies we hypothesized that subjects with cerebellar ataxia will demonstrate highly segmented movement profiles. We tested this hypothesis using a technique adopted from image analysis which essentially counts the number of high curvature transitions along a movement trajectory, hence the name high curvature analysis (HCA). As a secondary hypothesis, we expected that the integrated jerk over the duration of movement would be at least as good an indicator of smoothness of movement, and thereby serve as a means of gauging the sensitivity of the HCA technique. Although the HCA technique successfully discriminated between patients with cerebellar dysfunction and healthy controls ($P = 0.014$), the jerk analysis did not produce differences between groups that reached the 0.05 statistical level. We cannot conclude from this analysis, however, that integrated jerk is insensitive to cerebellar ataxia (indeed, an abundance of published data suggests otherwise). There are at least four possible explanations for this finding: (1) increased movement jerkiness was masked by CB patients’ tendency to have lower joint accelerations; (2) the jerk data were highly variable, due in part to noise magnification through the successive differentiation process, and coupled with a small sample size, may have resulted in an increased type II error rate; (3) the filtering procedure used to reduce the noise variability may also have eliminated high frequency information characteristic of irregular movements; and (4) jerk was probably higher at the end points but our calculations were over the whole range of motion thus reducing the effect of end-point jerk.

One difficulty in assessing movements in two or more dimensions is in obtaining a single score or performance measure. Time or frequency-domain techniques are performed separately on movements in each direction as if the movements were uncoupled, such as with the IAJ analysis. However, because the movements in the activity we present are coupled (the arm traverses an arc) we believe analysis of the movement trajectory is more appropriate and should better reflect the performance of the subject. Furthermore, apart from the HCA technique itself, the velocity trajectory is revealing and informative (compare Figs. 3 and 4), and may be useful for inclusion in clinical assessment reports of patients with cerebellar ataxia.

Although preliminary, our data suggest that the HCA technique may be useful for evaluating cerebellopathy rehabilitation outcomes and, on a broader level, rehabilitation efficacy. The technique has also been applied to center-of-gravity kinematics during a repeated bench step activity to assess rehabilitation outcomes in patients with vestibular dysfunction, and has shown promise as a sensitive measure of stability (unpublished observations). These data and our present results further suggest that the HCA technique may be very useful for quantifying ataxia or instability due to a variety of neurologic and motor control deficits.

Acknowledgements. Supported by the National Institute of Health (R01-AG11255), and the National Aeronautics and Space Administration through the NASA Cooperative Agreement NCC 9-58 with the National Space Biomedical Research Institute. We would also like to thank Dr. Herman Igo Krebs for his helpful comments.

References
