Is the velocity–curvature relationship disrupted in apraxic patients?

S. Jacobs,1,CA S. Hanneton,1,2 S. Heude1 and A. Roby-Brami1,3

1CNRS UMR 8119, 45, rue des Saints-Pères, 75006 Paris; 2UFR ST APS, Université René Descartes, 1 rue Lacretelle, 75015 Paris; 3Department of neurological rehabilitation, Hôpital Raymond Poincaré, AP-HP, Garches, France

CACorresponding Author: stephane.jacobs@biomedicale.univ-paris5.fr

Received 14 May 2003; accepted 24 June 2003

DOI: 10.1097/01.wnr.0000091307.5061.f6

Velocity and curvature of human movements are linked by a proportionality relationship (power-law) whose origin has been attributed either to functional properties of cortical areas or to peripheral constraints. 3D movements made by apraxic patients show a time-shift between velocity and curvature which has been considered as a disruption of the power-law, supporting the central hypothesis. We analysed the power-law in 2D drawing-like movements in healthy subjects and apraxic patients (correlation and cross-correlation analyses). The power-law remained preserved in apraxic patients, suggesting that the velocity–curvature relationship is not globally disrupted and thus that the power-law cannot be only attributed to central planning mechanisms in those associative brain areas injured in apraxic patients.

Key words: Apraxia; Drawing-like movements; Power-law; Velocity–curvature relationship

INTRODUCTION

Human curved movements are characterized by a tight relationship between the velocity of the end-effector’s trajectory and the geometric path that it describes [1]. This law has been quantified [2] as the two-third power-law. The power-law reflects, as does the minimum jerk for discrete point to point movements, a more general property of motor control in producing maximally smooth movement by minimizing a kinematic cost function [3–6].

The origin of this velocity–curvature relationship remains disputed since it has been attributed either to neural characteristics of motor planning or to peripheral constraints. The first argument favouring the central hypothesis is that the power-law is also observed when the subjects produce drawing trajectories by exerting isometric forces on a manipulandum [7]. Secondly, the geometrical and kinematic aspects of movement are also coupled in perceptual tasks [8,9]. In addition, neurophysiological recordings of motor and premotor cortical cells during spiral drawing showed that the population vector could code the variations of the hand velocity along the trajectory [10,11]. This could be linked to the time necessary to mentally rotate the intended movement direction [12].

Other authors suggest that the velocity–curvature relationship may result from constraints linked to the execution of movement. The power-law observed at the end-effector of the movement may result from the smoothness of periodic rotations in joint space [13], or to peripheral constraints due to limb dynamics and muscle mechanics [14,15].

In this context, disruption of the velocity–curvature relationship linked to a cerebral lesion would support the central hypothesis. Such a conclusion is suggested by the results obtained in ideomotor apraxic patients. Ideomotor apraxia is a disorder of higher motor control, which mainly affects skilled movements and tool use after a cerebral lesion involving the associative areas of the left hemisphere (in right-handers). Poizner and colleagues described abnormalities in movement kinematics in ideomotor apraxic patients, when performing or pantomiming complex 3D tool use movements [16–18]. There was a disruption of the spatial orientation of the movement, temporal abnormalities (i.e. abnormal movement initiation, delayed transitions and velocity irregularities) and a time-shift between the velocity and the radius of curvature (inverse of the curvature) [16,17]. The time shift, computed as delays between every single local minimum of the velocity profile and the nearest local minimum of the radius of curvature, has been interpreted as a global breakdown of the power-law.

However, this disruption of the velocity–curvature relationship might be specific to 3D tool use. We thus analysed 2D drawing-like movements, and performed statistical methods specifically designed to quantify a potential time-shift between velocity and radius of curvature.

PATIENTS AND METHODS

Patients: This study involved seven apraxic patients (five women and two men, mean age 56, range 31–73) and six
healthy subjects, (three women and three men, mean age 53, range 35–73). Apraxic patients had sustained a vascular accident in left parietal and/or frontal areas (1–6 months before the study).

All of these subjects were right handed. As apraxic patients suffered from mild to severe right hemiparesis, all the subjects performed the movements with their left arm.

**Tasks:** The participants were asked to follow, for 10 s, a shape (a circle or two different ellipses) drawn on a sheet of paper on a table in front of them, with their left index finger. The circle and the two ellipses had the same perimeter (40.2 cm), with two different ratios between the minor and major diameter of ellipses (0.67 for the round ellipse (R), 0.46 for the flat ellipse (F)). The instruction was to follow the contour of the pattern at a natural unconstrained velocity. Participants performed successively: circle, R then F ellipses horizontally oriented, circle, R then F ellipses vertically oriented.

**Data acquisition:** Movements were recorded using a Fastrack Polhemus™ magnetic sensor fixed on the left index fingernail (120 Hz). We checked that data were accurate (<1% error) within the workspace of the experiment.

**Data analysis:** The data from the sensor allowed the computation of curvature and tangential velocity of the movement [13]. They were then filtered using a gaussian low-pass filter with a cut-off frequency at 14 Hz.

In order to test the velocity–curvature relationship, we studied the correlation between the logarithm of the instantaneous tangential velocity and the logarithm of the instantaneous radius of curvature $\log(v(t))$ vs $\log(r(t))$ [2,14,15,19]. According to the power-law, the slope of the regression line (a) should be $\sim 0.33$.

This analysis was performed on the total movement sample and was repeated after segmentation of the trajectory, which proved necessary due to the temporo-spatial irregularities of the movement observed in apraxic patients. The segmentation was performed according to the minima of the velocity profile determined by manual pointing, and the statistical significance of the log-log correlation was tested within each segment (Pearson correlation coefficient).

In addition, cross-correlation analyses between tangential velocity and radius of curvature signals were performed within each segment of movement, in order to search for a time-shift between signals.

Non-parametric tests were used to compare the results of the log-log correlation analyses and the kinematic parameters of the movement segments between groups of subjects (Mann-Whitney test) and between movement shapes (Kruskall-Wallis test).

**RESULTS**

**General description of the movements:** Healthy subjects followed all the shapes smoothly and accurately (Fig. 1a). As expected, the velocity profile of the movements following the elliptical path showed regular periodic variations in parallel with the variations of the radius of curvature, and the minimal velocity occurred at the summit of the ellipse. As already observed [20], some periodic variations of the radius of curvature and of the tangential velocity were also observed for the movements following the circular path although the curvature of a circle is constant.

Five of the seven apraxic patients performed the task at a mean velocity similar to that of healthy subjects but with marked geometric and kinematic irregularities (Fig. 1b). The trajectory sometimes deviated from the prescribed shape and the velocity minima were only roughly situated around the summit of the ellipse. The velocity varied roughly in parallel with the radius of curvature, with some superimposed step-like variations from one lap to another and occasional interruptions of the periodic movement, with marked slowing down. The two other patients (BO and SA) produced particularly slow (maximum velocity 0.15 m/s) and irregular movements, without clear periodic variations of the velocity signal. The quantitative analysis of the trajectories rely only on the five apraxic patients that were able to produce consistent velocity variations.

The mean velocity of the movements was 0.39 ± 0.02 m/s in healthy subjects and slightly lower in the group of the five consistent apraxic patients (0.30 ± 0.02 m/s, Mann-Whitney test, $p = 0.002$). BO made movements at a mean velocity of 0.07 ± 0.002 m/s and SA at 0.05 ± 0.004 m/s.

**Correlation analysis and movement segmentation:** A correlation analysis between the instantaneous tangential velocity and the instantaneous radius of curvature was performed on the total trajectory sample. The correlation coefficient was always significant in healthy subjects, for all the shapes including the circles. Similar results were observed in the group of five consistent apraxic patients, whereas the correlation coefficient was not significant in BO and SA.

Due to the irregularity of the velocity profiles in apraxic patients, the path-following movements made by healthy subjects and by the five consistent apraxic patients were produced particularly slow (maximum velocity 0.15 m/s) and irregular movements, without clear periodic variations of the velocity signal. The quantitative analysis of the trajectories rely only on the five apraxic patients that were able to produce consistent velocity variations.

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segmented according to the minima of the velocity profile (black crosses on Fig. 1). Healthy subjects mostly performed the circles in two or three segments (31% and 65% of the cases, respectively) and the ellipses in two segments (93% for R and 100% for F ellipses). Apraxic patients performed the circles in two or three segments in 27% and 60% of the cases, respectively, and, most of the time, the ellipses in two segments (76% for R and 96% for F ellipses).

For the following analyses, we considered only the segments that were long and fast enough (>6 cm, <160 ms duration, peak velocity >0.2 m/s). This eliminated 0.3% of the segments in healthy subjects and 18.1% in apraxic patients leaving 1179 segments for analysis (387 in five apraxic patients, 792 in six healthy subjects).

The periodic variations of velocity were greater when following R ellipses and especially F ellipses than when following circles. Indeed, in both groups, the peak velocity increased and the minimum velocity decreased with increasing eccentricity of the shape (Kruskal-Wallis p < 0.0001). The peak velocity was significantly lower in apraxic patients (0.44 ± 0.006 m/s) than in healthy subjects (0.49 ± 0.005 m/s; Mann-Whitney p < 0.0001).

Log-log correlation analysis between velocity v(t) and radius of curvature r(t) was performed on each segment of movement. The results for the horizontally and vertically oriented ellipses were pooled together, since a preliminary analysis showed no correlation difference. The correlation coefficient between v(t) and r(t) was almost always significant in the selected segments (98.2% of the segments in healthy subjects, 97.1% in apraxic patients; Fig. 2).

However, the percentage of variance accounted for by the correlation (coefficient of determination R2) varied with the shape of the trajectory and the group of subjects (Fig. 3a). R2 was greater in ellipses than in circles, in both groups of subjects (Kruskal-Wallis p <0.0001). R2 was also greater in healthy subjects than in apraxic patients when drawing ellipses (Mann-Whitney p < 0.0001), and slightly greater in apraxic patients than in healthy subjects when drawing circles (Mann-Whitney p = 0.04). The slope of the regression lines also varied with the shape of the trajectory (Kruskal-Wallis p < 0.0001; Fig. 3b). The slope was significantly greater in healthy subjects than in apraxic patients when drawing ellipses (Mann-Whitney p = 0.01 for R ellipse, p < 0.0001 for F ellipse). The observed slope differed slightly significantly from the theoretical value of 0.33, except for apraxic patients drawing F ellipses.

Cross-correlation analysis was performed between the instantaneous velocity and the radius of curvature signals within the same sample of movement segments. This analysis checked for the presence of a possible time-shift between v(t) and r(t), by computing the delay between signals for which the correlation is maximal. The distribution of these delays was similar in healthy subjects and in apraxic patients (Fig. 4). In both groups, it followed a similar gaussian distribution and peaked around the null value (healthy participants: R ellipse: 0.00038 ± 0.018 s, F ellipse: 0.001 ± 0.011 s; apraxic patients: R ellipse: 0.002 ± 0.022 s, F ellipse: 0.001 ± 0.027 s). The mean delay was not different from zero in healthy subjects or apraxic patients, whatever the shape of the trajectory (non-parametric one sample test), showing that there was no time-shift between the velocity and the curvature of the movement.

**DISCUSSION**

The aim of the present study was to assess the occurrence of velocity–curvature relationship in apraxic patients. For this
purpose, we used a basic set-up that allowed performing 2D shape-following task with the fingertip without any interposed tool. Healthy and apraxic individuals performed this task without preliminary learning. This method was much coarser than the ones used in previous studies, which used tools such as pointers or digitising tablets and trained the subjects before recording [1,5,14,19]. Thus, we observed the spontaneous behaviour of the individuals when facing this task for the first time.

The results obtained in healthy subjects confirm the tight relationship between velocity and curvature when drawing ellipses. In contrast to what the power-law would predict, the circles were not followed at a constant velocity. When asked to produce circular trajectories, healthy subjects produced paths which had a segmented appearance, as if they tended to approximate the circle with usually three lower curvature elements [20]. The velocity varied in accordance with the power-law but the correlation coefficients were fainter and the slope lower for circles than for ellipses.

Apraxic patients made much less regular and smooth movements than healthy subjects. Two of them performed the task particularly slowly without identifiable periods. The five others were able to generate consistent movements, despite marked spatial (deviations of the trajectory from the shape) and temporal (segmented velocity profile with slowing down periods) irregularities. This is consistent with the fact that apraxic patients, when pantomiming complex gesture have difficulties in initiating the gesture and delayed the transitions between movement elements [16].

In healthy subjects, it is generally assumed that elliptical shape is generated by a continuous motor command, but it has been proposed that the control of more complex trajectories might be segmented [2,19]. Later studies showed that complex over-learned trajectories made by skilled healthy subjects could be generated by a continuous control [5,21]. The question of the continuous or discrete control is still open for more natural and spontaneous movements in healthy subjects.

The results presented here suggest that apraxic patients have difficulties in following an ellipse by generating continuous, smooth oscillations, but rather perform the task in a segmented way. A similar segmentation was observed in recovering hemiparectic stroke patients, when following a circular shape [22]. This eventuality of a segmented control in apraxic patients prompted us to analyse the velocity–curvature relationship on movement segments, identified according to velocity minima [22], in both apraxic patients and healthy subjects. This segmentation further documented the impairment of tempo-spatial organization of movement trajectories in apraxic patients, since about 18% of movement segments were too slow or too short to be attributed to a discrete motor command. Rather, these segments probably represent some delay before the onset of the next movement, and were rejected from further analysis.

Correlation between the instantaneous velocity and the radius of curvature showed that the power-law was valid in both healthy and apraxic individuals when considering the whole movement sample. This correlation was also observed after segmentation of the trajectory in almost all of the selected segments of movements. The slope of the regression lines were comparable in healthy and in apraxic participants. Cross-correlation analysis demonstrated that there was no time-shift between the velocity and the curvature signals.

In summary, the present study confirms the previous observations that apraxic patients show a tempo-spatial disorganisation of their movements. However, in the case of 2D drawing-like movements, this does not imply a disruption of the velocity–curvature relationship as demonstrated by correlation and cross-correlation analyses. This discrepancy between our results and those of Poizner et al. might be explained in several ways. First, the signal processing method used previously [16–18], which considered each single local velocity minimum, might have induced a bias, since the velocity profile of apraxic patients is much more irregular than that of control subjects. Second, the time shift they observed may be task-specific. The power-law has also been observed in 3D drawing-like movements in healthy subjects, but there are few detailed analyses [23]. On the one hand, performing 3D movements may by itself perturb apraxic patients, particularly in largely redundant non-constrained conditions, however our 2D unconstrained task also imposed to coordinate a redundant number of joint rotations. On the other hand, the integration of any tool into the movement imposes to displace the end-effector of the action from a part of the body (i.e. the tip of the finger) to the working point of the tool (i.e. pen, manipulandum, knife). Most of the studies on velocity–curvature relationship implicitly assume that healthy subjects automatically solve this problem. However, this is probably not the case in apraxic patients, who have specific difficulties in tool use.

In conclusion, we show that the velocity–curvature relationship is preserved in apraxic patients when performing simple 2D drawing-like tasks. Therefore, the power-law cannot be only attributed to central planning mechanisms in those associative brain areas injured in apraxic patients. It is more likely linked to motor execution but we cannot decide whether it is due to the function of the primary motor cortex and/or to subcortical interactions between the command and biomechanical constraints. Additional studies are needed to further analyse velocity–curvature coupling during 3D movements, particularly those involving the integration of a tool into the movement in healthy subjects and in apraxic patients.

REFERENCES
Acknowledgements: The authors are grateful to Professor Tamar Flash for stimulating discussions and comments on this text. We thank Pr B. Bussel and M. Combeaud for recruiting the patients. We are particularly grateful to the participants. A.R.-B. is supported by INSERM and AP-HP. S.J. holds a grant from French Ministry of Research (Cognitique).