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Kinematics invariance in multi-directional complex movements in free space: effect of changing initial direction

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Abstract

We investigated in normal human subjects the effect of changing the initial direction on the kinematic properties of figure '8' movement performed as fast as possible by the right arm extended in free space. To this end, the motion of the index finger was monitored by the ELITE system. The figure '8' movement was characterized by a complex tangential velocity profile (Vt) presenting 5 bell-shaped components. It was found that the temporal segmentation following Vt was not significantly different, whatever the initial direction of the movement. The decomposition of Vt into different velocity profiles with respect to vertical (3 phases, Iy–IIIy) and horizontal (5 phases, Iz–Vz) directions showed a significant relationship between the amplitude and the maximal velocity for all the different phases (except the IIy phase), which demonstrated a good conservation of the Isochrony Principle. However, we showed that the transition between the clockwise and counter-clockwise loop (inflection point) induced greater variability in the vertical velocity profile than in the horizontal one. Moreover, some parameters such as the maximal velocity of Iy and the movement amplitude of the last phases (IIIy and Vz) showed significant changes depending on the initial direction. A highly significant positive correlation was observed between the instantaneous curvature and angular velocity. This was expressed by a power law similar to that previously describe for other types of movement. Furthermore, it was found that this covariation between geometrical and kinematic properties of the trajectory is not dependent on the initial direction of movement. In conclusion, these results support the idea that the fast execution in different directions of a figure '8' movement is mainly controlled by two types of invariant commands. The first one is reflected in the 2/3 power law between angular velocity and curvature and the second one is represented by a segmented tangential velocity profile. © 1999 Elsevier Science Ireland Ltd. All rights reserved.

Keywords: Coordination; Kinematics; Multi-directional movement; Isogony principle

1. Introduction

For the formation of complex trajectories, the excess degree of freedom problem (Bernstein, 1967) poses a real challenge to the motor control theory. This is particularly crucial for cursive handwriting movements (Wada and Kawato, 1995). However, a number of simplification rules have been proposed, which greatly reduce the number of theoretical degrees of freedom of the system. Many authors have proposed dividing complex movements into simple segments. This segmentation may be based on muscle activation pattern (Denier van der Gon and Thuring, 1965) or on kinematic parameters (Morasso, 1981; Flash and Hogan, 1985; Flash and Henis, 1991). For instance, the bell-shaped velocity profiles described for rapid-aimed movement have been regarded as motor controlled variables (Atkeson and Hollerbach, 1985; Plamondon, 1995a,b). Other authors have proposed a segmentation into units of motor action reflecting the Isochrony Principle (Viviani and Terzuolo, 1982; Viviani and Cenzato, 1985). This type of segmentation based on the existence of stable covariations between geometric and kinematic properties of the trajectory have been applied to the analysis of drawing movement in two- or 3-dimensional free space or in isometric conditions (Viviani and Terzuolo, 1982; Lacquaniti et al., 1983; Soechting and Terzuolo, 1986, 1987a,b; Soechting et al., 1986). With this approach, Viviani and Terzuolo (1982) found that for handwriting and drawing, the tangential velocity (V_t) of the hand is inversely proportional to the curvature (C) of the path that it traces ($V = k/C$). Shortly thereafter, Lacquaniti et al. (1983) refined this relationship with a power law between angular velocity (A) and curvature of drawing movements ($A = kC\delta$), where k is the velocity gain factor as defined by Viviani and Cenzato (1985).

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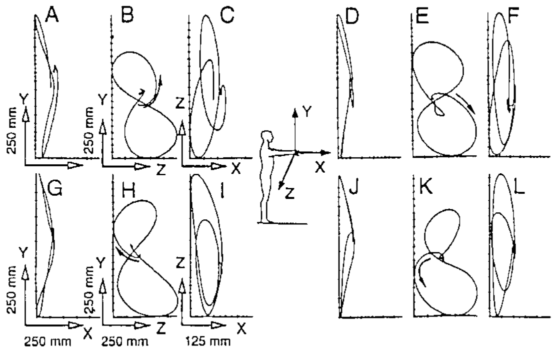

Fig. 1. Projections of the trajectories of the index marker during the drawing of figure '8' in the sagittal (A,D,G,J), frontal (B,E,H,K) and horizontal (C,F,I,L) planes, with upper-right (A–C), lower-right (D–F), upper-left (G–I) and lower-left (J–L) initial direction of movement. The central figurine represents the orientation of the axes with respect to a subject.

Each one of these approaches may be relevant to some aspects of motor programming and control. However, a major issue is how the different simplification rules can take into account the functional link between motor programming and execution of the movement in different environmental conditions. In the present study, we address some of these problems in reference to the figure '8' movement performed with diametrically opposed constraints imposed by the different initial directions of the movement. The present experiments were designed to explore: (1) the invariant properties of the velocity profiles and (2) the conservation of the covariation rules between geometrical and kinematic parameters in fast complex movements performed with diametrically opposed biomechanical constraints imposed by different initial directions of movement.

2. Materials and methods

2.1. Experimental design

4 right-handed male subjects aged between 21 and 40 years were asked to draw, as fast as possible, two series of '8' figures with the right arm extended in free space. A couple of minutes of rest were allowed between each movement. The movements were realized in the frontal field successively with an initial upper-right, lower-right, upper-left and lower-left direction (Fig. 1). The movements of the arm were recorded and analyzed using the optoelectronic ELITE system (Ferrigno and Pedotti, 1985). This system consists of two CCD-cameras detecting retro-reflective markers using a sampling rate of 100 Hz. The cameras were placed 4 m from the subject. 4 markers were attached to the arm (on the shoulder, the elbow, the wrist and the index finger). Velocity and acceleration signals were obtained by digitally differentiating position signals using a 5-point polynomial approximation.

As the movements were performed with the extended limb, the information from the 4 markers is partly redundant. The reconstruction of the arm movement by the ELITE system using the trajectories of the 4 markers confirmed the visual observation that the upper arm, forearm, hand and index finger acted as a rigid link. Thus, we used here the data with the best definition related to the representation of the figure '8': the position of the index marker.

2.2. Statistical analysis

First, we have statistically studied the tangential velocity profile (V_t) with respect to the initial direction of the movement. We grouped the data in 4 different sets whose initial direction was either: top (top-right, top-left), bottom (bottom-right, bottom-left), right (top-right, bottom-right) or left (top-left, bottom-left). We performed a cross-analysis between the top-bottom and right-left sets using the canonical correlation. If we want to explore the correlation between two sets of variables, the first one containing p variables and the second one containing q variables, the canonical correlation procedure will correlate the weighted sums for the two sets of variables (i.e. the linear combination of the p variables with the linear combination of the q variables). The determination of the weights is done so that the two weighted sums shall correlate maximally with each other. The canonical correlation thus, performs a canonical analysis based on the overall correlation matrix of all variables. In the terminology of canonical correlation analysis, the weighted sums define a pair of canonical variables; the squared correlation between the two canonical variables is also called the canonical root or canonical score (R).

Secondly, we explored the relationship between geometrical and kinematic properties of the trajectory, using a power law relating the instantaneous angular velocity (A(t)) and curvature (C(t)) (Lacquaniti et al., 1983):

$$A(\mathrm{t}) = k_1(C(\mathrm{t}))^{\delta} \tag{1}$$

C(t) is the rate of change of the direction of motion; k is the velocity gain factor as defined by Viviani and Cenzato (1985). From the instantaneous tangential velocity vector we compute the instantaneous tangent unit vector (μ_t) which is then differentiated

$$C = \frac{\left|\frac{\mathrm{d}\mu_t}{\mathrm{d}t}\right|}{V(\mathrm{t})} \tag{2}$$

where V(t) is the instantaneous tangential velocity.

Eq. (1) can also be written as a power law relating V(t) and the radius of curvature ($R(\mathrm{t}) = 1/C(\mathrm{t})$)

$$V(\mathrm{t}) = k_2(R(\mathrm{t}))^{1-\delta} \tag{3}$$

This latter relation is only valid for $R < \infty$. The exponent δ was computed using a log scale

$$ln(A) = lnk_1 + \delta lnC \tag{4}$$

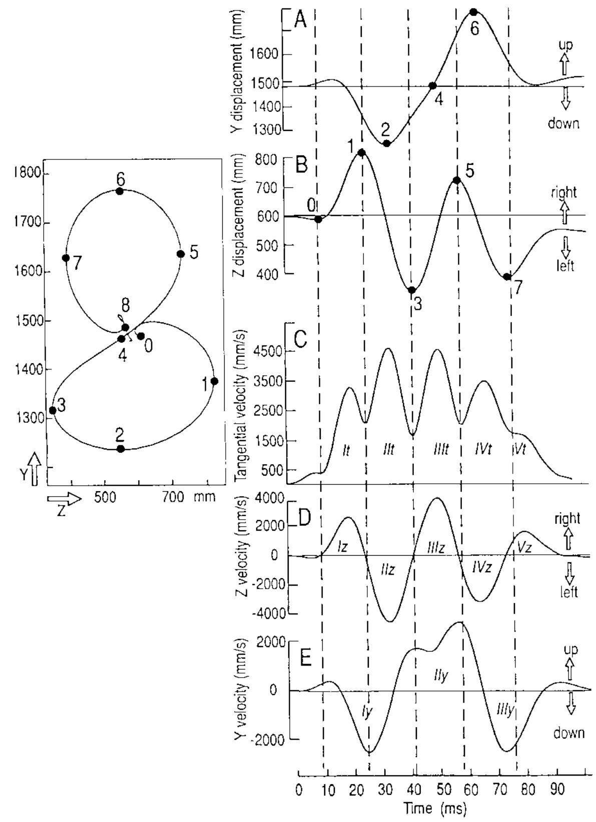

Fig. 2. Kinematics of the figure '8' started in the upper-left direction. Figural landmarks are indicated in a frontal view of the '8' and in the kinematic segmentation with respect to the vertical (Y) and horizontal (Z) directions for displacement (A,B) and velocity (D,E). Units of action are expressed in the tangential velocity profile (C) (I_t–V_t) and in the horizontal (D)(I_z–V_z) and vertical (E)(I_y–III_y) velocity profiles.

and in a similar way

$$ln(V) = lnk_2 + (1 - \delta)lnR \tag{5}$$

In practice we only treated the relationship between the angular velocity A(t) and curvature C(t) to avoid the mathematical problems due to the fact that the radius of curvature R(t) tends to $+\infty$ when the trajectory reaches a point of inflection. The strength of the relationship was determined using the correlation coefficient. Statistical analysis of the variance (ANOVA) and canonical correlation were made using the Statistica software (Statsoft©)

3. Results

3.1. General characteristics of the movement and effects of the initial direction on the velocity profiles

Fig. 1 illustrates the trajectories of the figure '8' performed with different initial directions. The figure '8' is only recognizable as such in the frontal (YZ) projection (Fig. 1B,E,H,K). Variation in the sagittal (XY) plane is small, and follows a curve whose radius corresponds to the extended arm length (Fig. 1A,D,G,J). Its contribution to the drawing of the figure '8' was not relevant, and therefore, it is not analyzed here. This sagittal pathway is stable whatever the initial direction of the movement.

Although the subjects were instructed to start the movement in the above mentioned directions, 65% of the executed movements commenced with a counter-movement. For example, for an instructed lower-right direction, the subject actually performed an initial small upper-left curve (Fig. 1E). The mean amplitude of the upper and lower directed counter movements were 65.8 ± 29.1 and 22.2 ± 10.3 mm, respectively.

The figure '8' movement can be divided on a simple geometrical basis, using the extreme points of trajectory: (0), the starting point (1), the first encountered lateral extreme (2), the first encountered vertical extreme (3), the second encountered lateral extreme (4), the inflection point between the two loops (5), the third encountered lateral extreme (6), the second encountered vertical extreme (7), the 4th encountered lateral extreme and (8), the finishing point. These points can be easily identified on the vertical (Fig. 2A) and horizontal (Fig. 2B) displacement traces. Alternatively, the figure '8' can be divided in different units of motor action on the basis of V_t. Fig. 2C shows the existence of 5 different velocity phases (I_t–V_t) and their temporal relationships with the preceding figural landmarks. As verticality of the long axis of the movement was preserved (angle of bissector between 1–7 and 3–5 segment relative to y axis ranged from −3 to +6°, mean of 0.9 ± 2.8°), V_t can be decomposed into vertical (V_y) and horizontal (V_z) components following the classical formula

$$(V_t = \sqrt{V_y^2 + V_z^2}),$$

without making the segments too sensitive to the rotation of the figure in the frontal plane. This decomposition disclosed the presence of 5 distinct phases along the z axis (phases Iz–Vz, Fig. 2D) and three phases along the y axis (phases Iy–IIIy, Fig. 2E). All these phases were characterized by bell-shaped velocity profiles, except for IIy for which two subcomponents were apparent around the inflection point of the figure '8'.

Fig. 3A illustrates for one subject the superimposition of V_t, profiles corresponding to the 4 different initial directions of the figure '8' movement. For each subject, the different directional sets (defined in the Section 2) are highly correlated (the canonical roots range between 0.95 and 0.98, mean of 0.97). This means that the different initial directions do not induce significant difference in the velocity profile. Fig. 3B and C show a good superimposition of the absolute velocity profiles V_y and V_z, respectively, except for the II_y phase which comprises the inflection point. This aspect is analyzed more closely on Fig. 4, which illustrates V_y (A) and V_z (C) around the inflection point (−70 ms to +70 ms) for all subjects and all movements. A similar bell shaped profile peaking at the

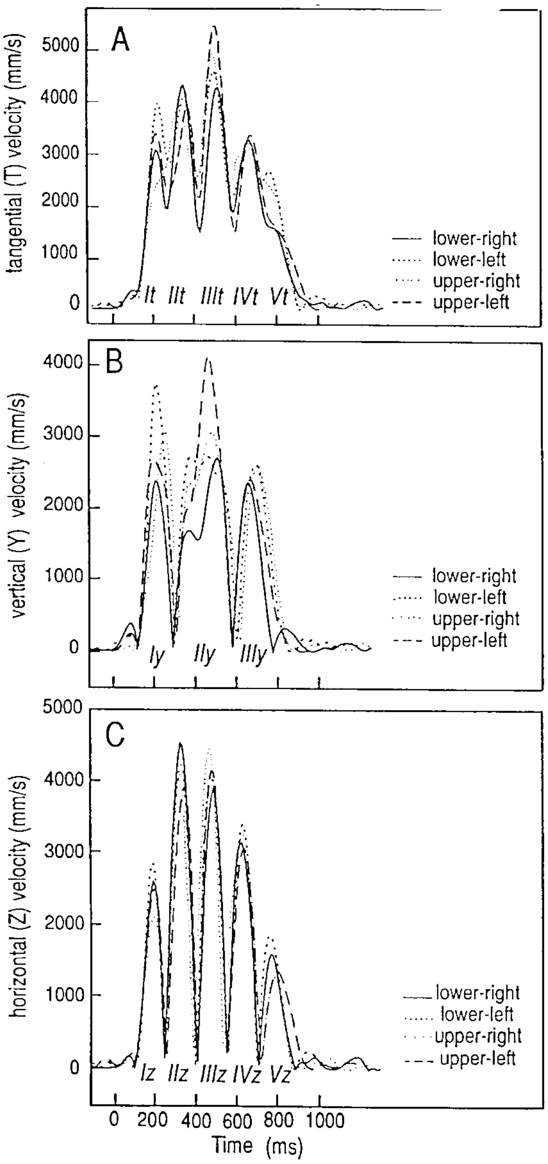

Fig. 3. Superimposition of the tangential velocity profiles (A), the absolute vertical (B) and horizontal (C) velocity profiles corresponding to the 4 initial directions in one representative subject.

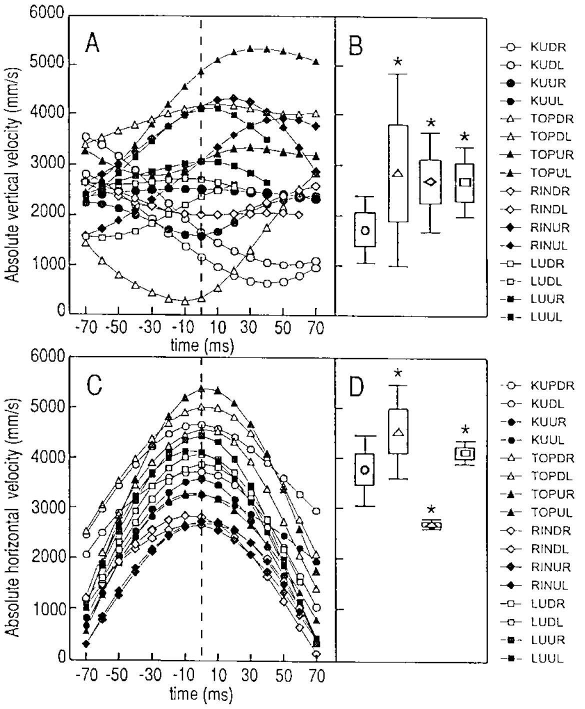

Fig. 4. Superimposition of the absolute vertical (A) and horizontal (C) velocity profiles around the inflection point (−70 to +70 ms) for all subjects and movements. The mean and standard deviation of Vy (B) and Vz (D) at the inflection point (0 ms) are presented for each of the 4 subjects (KUP, TOP, RIN and LU). The asterisk indicates statistical significance of ANOVA performed on the sets of standard deviations ($P < 0.001$). The boxes and the whiskers represent the standard errors and standard deviations, respectively. Abbreviations: DR, down-right; DL, down-left; UR, upper-right; UL, upper-left.

inflection point is observed for V_z while no consistent pattern appears for V_y. The similarity between velocity profiles in relation to the different initial directions can be expressed by the values of the standard deviation calculated for each experimental data point (every 10 from 70 ms before the inflection point to 70 ms after it). In order to compare the dispersion of V_y and V_z, one-way analysis of variance was performed on the sets of standard deviations. For each subject but one, the standard deviations of the Y and Z components differed significantly from each other ($F(1,28)$ values of 93.14, 68.09 and 42.40; $P < 0.001$). A significant difference was also found when all subjects and movements were considered together ($F(1,28) = 5.54$; $P < 0.02$). Fig. 4B and D show the means and standard deviations of V_y and V_z, respectively, all the inflection point for each subject, demonstrating significantly smaller values for V_z than for V_y for all but one subject.

3.2. Analysis of isochrony

One-way analysis of variance showed no significant difference in duration of all the different Y and Z velocity phases with respect to the initial direction of the movement (Table 1). The amplitude of the phases was measured as the difference between the position coordinates at the landmarks corresponding to the beginning and the end of each phase. Phase amplitudes were also well conserved except for the IIIy and Vz phases. The maximal velocity showed no significant difference except for Iy. The amplitude of the last velocity phase in Y direction (IIIy) was significantly lower when the movement was initiated in the downward direction ($F(3,28) = 6.07$; $P < 0.002$). The amplitude of the last velocity phase in Z direction (Vz) was significantly lower when the movement was initiated to the right ($F(3,28) = 4.78$; $P < 0.008$). The maximal velocity of the Iy phase was significantly lower when the movement was initiated upwards ($F(3,28) = 5.64$; $P < 0.03$). Whatever the initial direction of the movement, a highly significant correlation was found between the maxi-

Table 1
Kinematic parameters of the figure '8' with respect to the initial direction (mean ± SD)[a]

A initial direction	AMAX Iy	AMAX IIy	AMAX IIIy	AMAX Iz	AMAX Iiz	AMAX IIIz	AMAX Ivz	AMAX Vz
UR	356 ± 86	698 ± 126	381 ± 79	247 ± 98	375 ± 98	365 ± 170	394 ± 181	176 ± 54
UL	371 ± 43	761 ± 76	458 ± 67	244 ± 71	392 ± 102	379 ± 109	364 ± 56	223 ± 47
LR	399 ± 84	667 ± 77	335 ± 37	269 ± 52	461 ± 67	425 ± 133	359 ± 126	139 ± 41
LL	458 ± 95	732 ± 135	350 ± 60	236 ± 46	410 ± 99	427 ± 117	351 ± 120	220 ± 61
ANOVA	$F = 2.54$	$F = 1.16$	$F = 6.07$	$F = 0.33$	$F = 1.28$	$F = 0.44$	$F = 0.16$	$F = 4.78$
$P = 0.076$	$P = 6.341$	$P = 0.002$	$P = 0.800$	$P = 0.298$	$P = 0.723$	$P = 0.917$	$P = 0.008$	
B initial direction	DUR Iy	DUR IIy	DUR IIIy	DUR Iz	DUR IIz	DUR IIIz	DUR IVz	DUR Vz
UR	225 ± 45	308 ± 49	298 ± 60	173 ± 37	162 ± 23	150 ± 25	180 ± 29	186 ± 21
UL	221 ± 27	337 ± 77	348 ± 94	180 ± 18	171 ± 17	172 ± 25	201 ± 47	255 ± 86
LR	203 ± 19	361 ± 52	291 ± 103	175 ± 30	177 ± 12	176 ± 25	186 ± 34	212 ± 70
LL	197 ± 16	343 ± 56	268 ± 34	185 ± 54	177 ± 24	170 ± 33	170 ± 23	200 ± 38
ANOVA	$F = 1.60$	$F = 1.07$	$F = 1.49$	$F = 0.15$	$F = 1.00$	$F = 1.44$	$F = 1.11$	$F = 1.95$
$P = 0.211$	$P = 0.378$	$P = 0.237$	$P = 0.929$	$P = 0.409$	$P = 0.250$	$P = 0.360$	$P = 0.143$	
C initial direction	VMAX Iy	VMAX IIy	VMAX IIIy	VMAX Iz	VMAX Iiz	VMAX IIIz	VMAX Ivz	VMAX Vz
UR	3114 ± 735	3478 ± 708	2702 ± 474	2769 ± 1018	3731 ± 1065	3706 ± 1191	3359 ± 1210	1643 ± 371
UL	2625 ± 145	3612 ± 899	2829 ± 888	2503 ± 805	3594 ± 809	3493 ± 765	3025 ± 604	1741 ± 620
LR	3320 ± 718	3289 ± 554	2206 ± 464	2905 ± 588	4112 ± 780	3706 ± 874	3091 ± 900	1290 ± 435
LL	3920 ± 743	3180 ± 429	2.368 ± 376	2677 ± 604	4150 ± 1002	3997 ± 778	3234 ± 934	1998 ± 414
ANOVA	$F = 5.64$	$F = 0.67$	$F = 1.94$	$F = 0.38$	$F = 0.72$	$F = 0.40$	$F = 0.20$	$F = 3.11$
$P = 0.003$	$P = 0.573$	$P = 0.144$	$P = 0.768$	$P = 0.548$	$P = 0.750$	$P = 0.893$	$P = 0.052$	

[a] Abbreviation: UR, upper-right; UL, upper-left; LR, lower-right; LL, lower-left. AMAX, maximum amplitude (mm); DUR, duration (ms); VMAX, maximum velocity (mm/s); *shows statistical significance.

mal velocity and amplitude for each phase, except for IIy (Table 2). This latter finding is clearly illustrated in Fig. 5 in which linear regressions are presented for each phase. Regressions are calculated for all movements (all subjects and initial directions) and individual values are represented with different symbols according to the initial direction, in order to verify the conservation of the regression. As the experimental instruction did not include any amplitude requirements, some degree of variation in phase amplitude was observed within and between subjects. The slope of the amplitude-velocity relationships was remarkably stable in all phases but IIY ($7.5 \pm 2.3\ s^{-1}$).

Table 2
Linear correlation of the maximal amplitude–velocity relationship for the y and z phases of movement[a]

		Iy	IIy	IIIy	Iz	IIz	IIIz	Ivz	Vz
UR	R	0.94	0.25	0.89	0.98	0.90	0.97	0.97	0.93
	S	8.07	1.40	5.35	10.18	9.74	6.80	6.49	6.37
UL	R	0.68	0.07	0.92	0.97	0.92	0.89	0.49	0.86
	S	2.29	− 0.90	12.06	11.04	7.31	6.29	5.20	11.34
LR	R	0.77	0.60	0.55	0.84	0.95	0.92	0.93	0.73
	S	6.56	4.32	6.92	9.34	11.00	6.04	6.64	7.60
LL	R	0.85	0.85	0.80	0.87	0.63	0.80	0.94	0.92
	S	6.66	2.70	4.99	11.18	6.44	5.28	7.25	6.24
All	R	0.83	0.32	0.79	0.93	0.81	0.90	0.91	0.84
	S	7.49	1.99	6.32	10.33	7.89	6.14	6.60	7.26

[a] R, correlation coefficient; S, slope of the linear repression.

3.3. *Effects of the initial direction on the geometrical to kinematic relationship*

The relationship between the angular velocity and the curvature is illustrated for one subject in Fig. 6A and B. The correlation is very good. For all the subjects and movements the mean r value is 0.92 and range from 0.84 to 0.97. In this condition, the δ exponent is a reliable measure of the geometrical to kinematic relationship of the movement. The mean value of is 0.83 ± 0.09. We tested the coherence of the exponent values δ with respect to the initial direction of the movement. This was done using single ANOVA measure which showed no significant difference between the values ($P = 0.59$). This measure verified that there was no systematic changes in the exponent values as a function of the initial direction of the movement. When calculated with the approximation of the 2/3 power law, the velocity gain factor (k) plotted in function of time was a wing-shaped trace for which the only common characteristic of the different profiles was the nadir of the trace, which corresponded to the inflection point. Neither before or after this nadir did k show any constancy or variation related to the 5 phases of V_t.

4. Discussion

This study demonstrates that the kinematic segmentation of the fast execution of single figure '8' into different

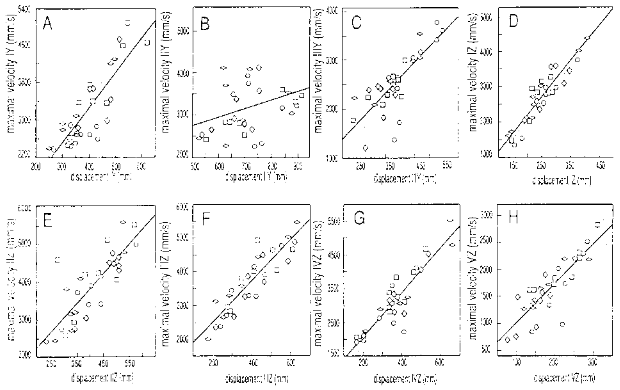

Fig. 5. Linear regressions of the maximal amplitude-velocity relationships for each phase of the figure '8' movement for all subjects and directions. os = lower-left initial direction; ud = upper-right initial direction; oc = upper-left initial direction; od = lower-right initial direction.

tangential velocity phases shows no significant difference, whatever the initial direction of movement. Preservation of kinematic parameters had been found for repetitive clockwise and counter-clockwise drawing of figures with no inflection points (Soechting et al., 1986). This preservation concerned the phase relation between orientation angles between segments of the arm. This problem has not been addressed in the present study, as we confined the movement to one joint and 3 degrees of freedom.

The study of the single execution of a complex movement as opposed to repetitive execution of the same figural pattern, aimed at extending the conceptual framework adopted for point-to-point simple movements (Gottlieb et al., 1989) to the realization of more complex trajectories. Following the same rationale, subjects were instructed to perform the movement as fast as possible in the hope that the same optimization procedures would be involved (Happee, 1980; Hannaford et al., 1985; Cheron and Godaux, 1986). For unrestrained vertical point-to-point arm movement, the tangential velocity profile has been shown to be invariant when normalized for speed and load (Atkeson and Hollerbach, 1985). This invariance is interpreted as a reflection of the underlying arm dynamics (Hollerbach and Flash, 1982). In the case of single figure '8' drawing, performed at high speed, our findings are consistent with those of Morasso and Mussa Ivaldi (1982) who described 5 successive bell-shaped subcomponents in the tangential velocity profile. These correspond to the underlying chain of strokes for building the movement. For repetitive slow-paced figure '8' movements, Soechting and Terzuolo (1987b) described only two components in the tangential velocity profile per complete figure in most recorded movements. However, additional components were found when some flattening of the loops occurred.

The dissociation of the tangential velocity profiles into their vertical and horizontal components is motivated by the fact that the instruction is expressed in a reference frame defined by the vertical and horizontal directions. Moreover, it reflects the relation of movement to gravity (y axis) and to the trunk mass (z axis) which are possible factors that may influence the execution of movement (Gurfinkel et al., 1993; Papaxanthis et al., 1998).

Another motivation for placing more emphasis on Vz and Vy was that we recently found that the same figure '8' movement can be learned by an artificial neural network when it is fed with raw EMG signals and mapped to Vz and Vy (Cheron et al., 1996). This segmentation enabled us to show that there is no significant difference in the duration of all the different phases, whatever the initial direction of movement. Moreover, the highly significant relationship between the amplitude and the maximal velocity for all the different phase, (except for IIy phase) extends the Isochrony Principle largely demonstrated in different movements, by correlating the increase in average velocity with the linear extent of the unit of motor action (Viviani and Terzuolo, 1982; Viviani and McCollum, 1983; Viviani and Flash, 1995). This applies even though different muscle

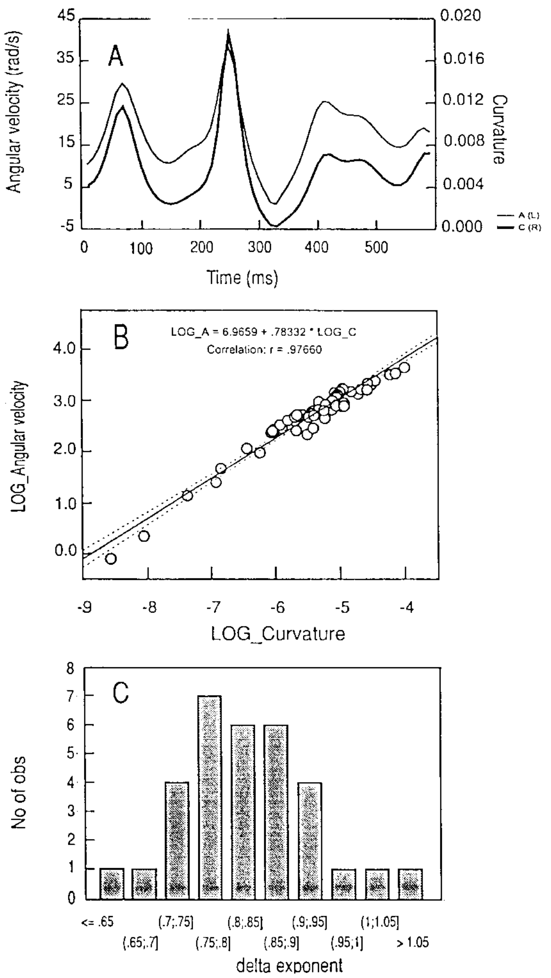

Fig. 6. Kinematics to geometrical relationship in one representative subject. Superimposition of the angular velocity and the curvature of the figure '8' movement (A). The slope of the linear regression between these two variables (B) corresponds to the δ exponent. In C, distribution of the δ exponent calculated for all subjects and for the 4 different initial directions.

actuators are involved, with different activation sequences, and length variations evolve differently.

The absence of a significant correlation between the maximal amplitude and velocity for IIy phase is explained by the presence of two subcomponents of the velocity profile of this phase (Figs. 2 and 3B). This represents a particular constraint of the figure '8' which is also indexed by the step change in the velocity gain factor (k) (Viviani and Cenzato, 1985). Indeed this phase corresponds to the transition between the upper and the lower loop of the '8' whose central dynamic management is expected to be more complex, as demonstrated in the mental rotation of neuronal population vector (Georgopoulos et al., 1989). It is interesting to note that this transition between clockwise and counter-clockwise is only reflected in the vertical IIy phase and does not disturb the corresponding horizontal velocity profile. This seems to indicate the prevalence of the horizontal agonist–antagonist motor actions on the vertical ones for producing the oblique trajectory of the longest phase of the '8'.

In spite of the temporal invariance of the velocity profiles, some parameters of the free rapid movement used in this study showed significant changes depending on the initial direction. The most interesting effect is the increase in the maximal velocity of the first phase (Iy) when the movement was initiated downward. The fact that the maximal velocity of the other phases, and more particularly the horizontal ones, are not influenced by the initial direction indicates the existence of a facilitatory effect played by gravity at the very beginning of the movement. This is in accordance with the recent study of Papaxanthis et al. (1998), indicating a greater acceleration for downward movements of the arm than for upward movements. The significant difference of the amplitude of the last phase (IIIy, Vz) could also be explained for IIIy by the gravity constraint (when the movement was initiated downwards the amplitude of the upper loop of the '8' decreased). The reduction of the amplitude of the last horizontal phase (Vz) when the movement was initiated to the right could be explained by the presence of the trunk mass which limited the horizontal movement directed to it (to the left in the case of a movement performed by the right arm).

Some authors have considered segmentation of the figure '8' into two units of action separated precisely at the inflection point on the basis of the velocity gain factor, which remained approximately constant within each segment (Viviani and Cenzato, 1985). The movement presently studied cannot be segmented in this way as proposed for repetitive movements by Viviani and Cenzato (1985), since the accelerations at the onset and at the end of the movement preclude the analysis of steady state values which would be representative of the execution of the movement.

The preservation of the first phase duration has strong implications as it is not influenced by the preceding trajectory and it depends much less on viscous and elastic parameters than the subsequent phases. Therefore, it constitutes a greater challenge over gravity which varies widely whether the movement is directed upwards or downwards. Conservation of its velocity profile suggests that external constraints such as gravity are integrated in the command system, which would work mainly as a feedforward control system. The counter-movement observed in this first phase of movement must not be interpreted as a gravitational release of muscle activity when the movement is primed. Indeed counter-movements are evident for all initial directions, including downward launching of the arm. They may actually be a reflection of a stored pattern implicating the prevalence of shape over the initial directional requirement.

The preservation of the 2/3 power law between angular velocity (V) and the curvature (C) of the present movement proves that the covariation between geometrical and kinematic properties of the trajectory is also respected in these very fast movements. Interestingly, the distribution of the present δ exponent with a mean of 0.83 ± 0.09 is very similar to those reported by Massey et al. (1992) for drawing movement in isometric conditions (δ mean of 0.76 ± 0.09). Moreover, in the present experiment, changing initial direction has no significant effect on the δ exponent. The stability of the δ exponent in spite of large differences in biomechanical factors, such as those involved when the initial direction is diametrically opposed or when the movement is performed in isometric conditions (Massey et al., 1992), confirms the idea that the covariation between geometrical and kinematic parameters is mainly of central origin. As suggested in a developmental study by Viviani and Schneider (1991), the 2/3 power law and isochrony may be progressively imposed, through learning, on an unconstrained initial state.

In conclusion, our study demonstrates that for rapid execution of a single figure '8' movement the Isochrony Principle and the 2/3 power law between angular velocity and curvature are respected, and that the tangential velocity profile is an invariant relative to the initial direction of movement. However, decomposition into vertical and horizontal components highlights variability in vertical but not horizontal velocity profiles around the inflection point

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