

A NON-LINEAR ANALYSIS OF KINEMATIC VARIABILITY DURING CYCLIC REACH-AND-POINT MOVEMENTS

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INTRODUCTION

Human voluntary movements are highly variable. For example, the most reproducible feature of the trajectories of multi-joint reaching movements is the lack of reproducibility (Latash, 1988). Variability exists at multiple levels of movement organization and is a result of the degrees-of-freedom coordination problem formulated by Bernstein (Latash, 1988).

Variability during reaching movements has been examined to provide insight into movement planning, execution, and outcome. This variability has typically been quantified using traditional statistical methods (e.g., Abend et al.; 1982; Atkeson and Hollerbach, 1985). Unfortunately, traditional methods of statistical analysis can skew or even mask the degree of variability involved in skilled movements (Stergiou, 2004). Therefore, the use of non-linear analytical techniques to provide a more complete analysis of kinematic variability during reaching movements is necessary.

The purpose of this study was to use a non-linear approach to examine kinematic variability during reach-and-point movements. While Burdet et al. (2006) used non-linear tools to assess variability during discrete, two-dimensional reach-and-point movements, the present study was the first to analyze variability during cyclic, three-dimensional reach-and-point movements using a non-linear time series analysis.

METHODS

Twelve healthy, right-arm dominant individuals (6 males, 6 females) between 20-40 years of age participated in this study.

After undergoing informed consent procedures, participants were seated in front of a target grid oriented in the frontal plane. The center of the target grid was placed at 75% of maximum reach distance and aligned with the center of the shoulder joint for all individuals. The 3-cm diameter targets were positioned 25 cm apart to allow the subjects to perform point-to-point reaching movements with their dominant arm in two directions (horizontal and vertical) at two frequencies (1.0 and 2.0 Hz). A motion capture system (Visualeyez VZ3000, PhoeniX Technologies) was used to record the three-dimensional position of the fingertip for 30 movement cycles. The 4 conditions (2 directions \times 2 frequencies) were presented in random order.

Kinematic variability was quantified by calculating the Lyapunov exponent (LyE) for consecutive trajectories in time-delay phase space. The LyE values were calculated using Chaos Data Analyzer software (Version 1.0, Physics Academic Software). A factorial ANOVA design was used to assess the effects of movement direction and movement frequency on kinematic variability for all three axes (medial-lateral [M-L], anterior-posterior [A-P], and superior-inferior [S-I]) of motion.

RESULTS AND DISCUSSION

A non-linear analysis of kinematic variability during cyclic reach-and-point movements yielded several key findings. First, the main effect of movement direction on LyE values was not significant ($F_{1,11} = 1.30, P=0.28$); variability did not differ between the horizontal and vertical movement directions (see Table 1). This contrasts with the finding of increased variability during vertical movements using traditional linear methods (Abend et al., 1982; Atkeson and Hollerbach, 1985).

Second, the main effect of movement frequency on LyE values was significant ($F_{1,11} = 65.32, P<0.0001$); variability was greater during the 2.0 Hz conditions than the 1.0 Hz conditions (see Table 1). This also contrasts with the finding of velocity profile invariance using traditional linear methods (Abend et al., 1982; Atkeson and Hollerbach, 1985).

Third, the main effect of movement axis on LyE values was significant ($F_{2,12} = 224.77, P<0.0001$). The fingertip trajectories along the primary movement axis (M-L and S-I axes for the horizontal and vertical movement directions, respectively) exhibited less variability than the fingertip trajectories along the secondary movement axes (A-P/S-I and M-L/A-P axes for the horizontal and vertical movement directions, respectively).

Table 1: LyE values (mean \pm SD) for consecutive trajectories in time-delay phase space along the M-L, A-P, and S-I axes of movement as a function of movement frequency and movement direction during cyclic reach-and-point movements.

Movement Frequency	Movement Direction	Movement Axis		
		M-L	A-P	S-I
1 Hz	Horizontal	0.066 \pm 0.021	0.238 \pm 0.081	0.203 \pm 0.072
	Vertical	0.231 \pm 0.035	0.223 \pm 0.037	0.079 \pm 0.011
2 Hz	Horizontal	0.141 \pm 0.031	0.293 \pm 0.095	0.276 \pm 0.068
	Vertical	0.315 \pm 0.023	0.308 \pm 0.037	0.128 \pm 0.013

SUMMARY

Kinematic variability during cyclic, three-dimensional reach-and-point movements was assessed using the LyE, which is a measure of local dynamic stability (Burdet et al., 2006). Since local dynamic stability is critical for successful movement execution and this information cannot be assessed through traditional linear methods for quantifying kinematic variability, the use of non-linear analysis is necessary to identify the true structure of variability during reaching movements. The results of this study provided a more complete analysis of kinematic variability during reaching movements than that obtained through the use of traditional linear methods. Future research will focus on the functional role of kinematic and kinetic variability and the characterization of mechanisms by which humans ensure local dynamic stability during cyclic movements.

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