Movement Intermittency and Variability in Human Arm Movements

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Human reaching and tracking movements exhibit a multi-peaked speed profile which is commonly interpreted as evidence for submovements. As the movement gets slower, the individual peaks stand out more distinctly, accompanied by an increase in the number of the peaks. This phenomenon corresponds to non-smoothness or intermittency in the movement. In this study, we evaluate two potential sources proposed in the literature for the origins of movement intermittency and conclude that intermittency is more likely due to noise in the neuromuscular system as opposed to a central movement planner that generates intermittent plans. We also discuss our results' relevance to movement variability and noise models.

Doeringer and Hogan [1] proposed two possibilities as the source of intermittency: (1) A central movement planner that utilizes (simple) submovements to generate plans for complex movements. (2) Noise getting imposed on the plan along the neuromuscular circuitry. Although they did not arrive at a final conclusion on the source of intermittency, they stated that interpreting peaks in tangential speed profiles as incomplete blending of submovements would lead to a conclusion favoring the central planner option.

We hypothesize that movement intermittency evaluated at various locations along the human arm during a constant speed tracking task will increase in the distal direction. If verified, this increase in distal direction indicates noise as the major source of intermittency since the most natural explanation is a noise mechanism; the intermittency would be amplified due to additional noise being interjected (through joint rotations connected in a serial fashion) along the arm in the distal direction. In contrast, intermittency in the original movement plan would be expected to produce similar intermittency levels for all joints along the arm. We have designed an experiment to test our hypothesis.

In the experiment, five participants completed a circular tracking task by tracking a pointer on an LCD screen with their fingertip. All participants provided informed consent approved by the Institutional Review Boards of both institutions. Motion capture markers were attached on the bony parts of the arm on the shoulder, elbow, wrist joints and on the nail of the index finger as illustrated in Fig. 1. 3D trajectories of the markers were recorded using a Vicon motion capture system with ten high resolution MX 40 cameras at a sampling rate of 50 Hz.

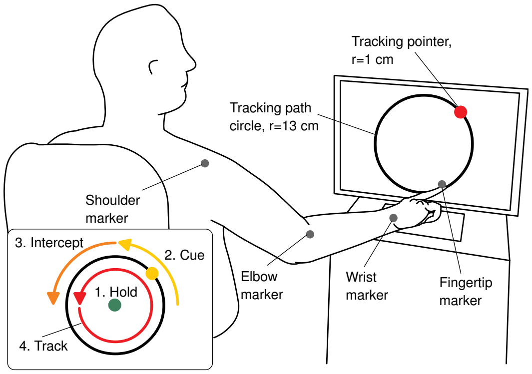

Fig. 1. An illustration of a participant in the experimental setting with attached motion capture markers. Insert at bottom left: The trajectory that the tracking pointer follows as a trial progresses through the four phases: (1) pointer at the center during the hold phase, (2-4) pointer changing colors and moving on the tracking path with constant speed during the cue, intercept and track phases.

The experiment consisted of two sessions of 25 trials each. Computer screen orientation (*vertical/horizontal)* was changed between the sessions. The screen was in a normal position in the vertical case and it was lying on the table facing up in the horizontal case. The order of presentation of these cases to each participant was determined randomly. The speed of the pointer to be tracked changed randomly among trials, but it was constant within a trial. Tracking speed had five levels: 2.5 cm/s, 3.75 cm/s, 5 cm/s, 12.5 cm/s and 25 cm/s. Each speed level was experienced five times in each session. Each trial consisted of four phases as schematically shown in the insert on the bottom left on Fig. 1. Our visual interface design was adapted from Pasalar et al. [2]. A total of 250 trials (12 of which were identified as incomplete trials and excluded from analyses) constituted the data set corresponding to 5 participants × 5 speed levels × 5 trials for each speed level × 2 orientation levels.

In addition to the original data set, we generated a decoupled set where the positions of each of the four markers were replaced by the difference in position of two consecutive markers, proximal position subtracted from the distal one. The purpose of the decoupling was to be able to create fair comparison conditions for intermittency of different markers. To better illustrate the coupling effect, note that movement of the shoulder would be a base movement for the elbow, hence effecting the kinematic variables in elbow data which is recorded with respect to a fixed world coordinate system.

Both data sets were filtered with a zero phase-shift second order low-pass Butterworth filter with a cut-off frequency of 5 Hz. Velocity in each axis was calculated using a backward

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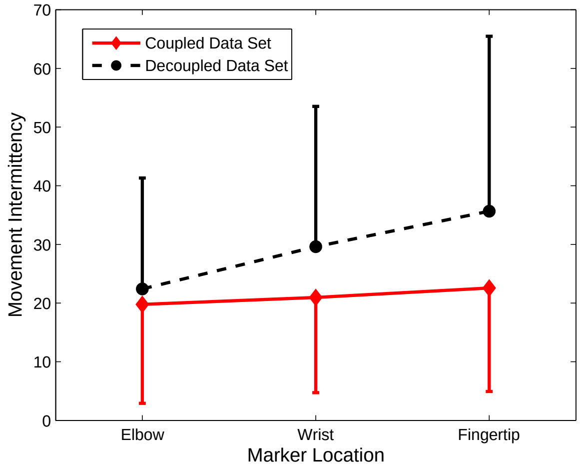

Fig. 2. The mean and standard errors of movement intermittency for all trials corresponding to the markers are plotted to illustrate the increasing intermittency trend in distal direction. The trend is more pronounced in the decoupled data set. Based on the results of the paired sample t-test, for all pairs of markers within the same data set, the distal marker intermittency is significantly higher than that of the proximal one ($p < 0.05$). Movement intermittency is quantified as number of peaks in tangential speed profile. Note that the reason for high variance presented in the plot is that because all trials with all five different speed levels are lumped together for this plot, while the t-test follows a paired sample procedure where each data point for a marker is compared with the other marker under completely equivalent conditions.

difference method. As the measure of intermittency, we used the number of peaks in the tangential speed profile, similar to the measure used by Kahn et al. [3].

To compare the movement intermittency of different markers, we used a standard two-tailed paired-sample t-test, results of which are given in Fig. 2. Within the decoupled data set, a significant difference between means exists for elbow vs. wrist, elbow vs. fingertip and wrist vs. fingertip [$t(237) < 0, p < 0.001$ in all cases]. Similar results are obtained using the original data set. All six pairwise comparisons of movement intermittency at different points on the arm resulted with significantly higher intermittency for the more distal point.

Results of a multivariate ANOVA analysis (details not given due to space constraints) for the fingertip marker using the decoupled data indicate that intermittency decreases for higher speed levels, and the main effect of speed on intermittency is found to be statistically significant. Data for the main effect of tracking plane orientation and for the interaction effect of speed by orientation on intermittency failed to show significance. These results imply that intermittency characteristics of movements highly depend on the average movement speed but are considerably less sensitive to the orientation of the actual movement plane in the task space.

The fact that significant increases in movement intermittency are observed for points located along the distal direction on the arm supports a neuromuscular noise alternative versus a discrete central movement planner hypothesis as an explanation for the movement intermittency.

One alternative explanation for the observed increase of intermittency in distal direction could be the biomechanics of the arm. Proximal parts (such as the upper arm) of the arm has more inertia than the distal portions (hand or fingers). Impedance properties are also different for different joints of the arm. The arm acts as a low-pass filter for the torques applied on the joints, and the proximal parts are expected to have a lower cut-off frequency than the distal parts. This can lead to the varying levels of intermittency along the arm, even when the torques applied on the joints are identical in terms of the intermittency content. However, we believe that since the speed conditions in our experiment are concerned with considerably slow movements, the range of speeds covered in our study is below the cut-off frequencies of the arm joints, hence an explanation based on arm dynamics would not be valid.

It should be noted that our results do not rule out the possibility that central planning generates movement plans with different intermittency levels for different joints. However we believe that plans with similar intermittency content for different joints along the arm are more plausible than plans that are tailored specifically for each individual joint.

In what follows we briefly discuss our results in relation to recent findings on movement variability. There is a similar debate on the origins of movement variability in the neuroscience field. Proposed sources are central planning noise versus execution noise. van Beers et al. [4] demonstrated that execution noise is the major factor causing movement variability by using a noise model based on three noise sources: signal dependent noise (SDN), constant noise and temporal noise. Our finding that noise increases in the distal direction is an indication of execution noise domination and supports this argument. In contrast, Churchland et al. [5] argued that movement planning noise should also be considered as a significant factor on overall variability, indicating that such planning variabilities can involve controller customizations for the upcoming movement. This idea was motivated by the observation that changing movement directions in the experiments in [4] led to change in kinematics and dynamics of the arm. However, in our experiments, the kinematics and dynamics do not change since the same circular path is tracked in all trials, yet the movement intermittency is significantly different for different speed levels. This further supports findings reported by van Beers et al. [4].

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