

Intermittency of Slow Arm Movements Increases in Distal Direction

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Abstract—When analyzed in the tangential speed domain, human movements exhibit a multi-peaked speed profile which is commonly interpreted as evidence for submovements. At slow speeds, the number of the peaks increases and the peaks also become more distinct, corresponding 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. This conclusion is based on the assumption that the central planner would be expected to introduce similar levels of intermittency for different joints, while accumulating noise in the neuromuscular circuitry would be expected to exhibit itself as increase in noise in distal direction. We have used a 3D motion capture system to record trajectories of fingertip, wrist, elbow and shoulder as five participants completed a simple manual circular tracking task at various constant speed levels. Statistical analyses indicated that movement intermittency, quantified by a number of peaks metric, increased in distal direction, supporting the noise model for origins of intermittency. Movement speed was determined to have a significant effect on intermittency, while orientation of the task plane showed no significance.

Index Terms—Movement intermittency, human motor control, robotic rehabilitation, submovements.

I. INTRODUCTION

The human motor control system is able to generate movements with great agility, dexterity, precision and compliance. Furthermore, the motor control system is immensely flexible, allowing humans to adapt to novel environments to regain normal movement patterns [1]. This adaptability also enables humans to become adept at motor skills through training and learning. Because of these attractive properties, the human motor control system has significantly influenced research and design of robotic motor control systems, particularly in the domain of humanoids. Still, there are many aspects of motor control in humans that are not completely understood or even appreciated [2]. We closely examine one such aspect in this paper, the intermittent or non-smooth nature of movements that become especially evident during considerably slower than normal movements.

It is well-known that the speed profile of a movement trajectory includes distinct peaks. These peaks are frequently interpreted as an indication for the underlying blended

submovements that form up the total movement [3], [4]. These peaks become more pronounced as the average speed of the movement decreases, thereby resulting in decreased movement smoothness. Due to the emergence of almost distinct peaks, the movement appears to be intermittent. Throughout the article, we use the term “intermittency” as an equivalent to “non-smoothness”, since intermittency is assumed to be quantifiable for all speed profiles, including those where the peaks are not entirely isolated or distinct.

In their study on the origins of movement intermittency, Doeringer and Hogan [5] propose two possibilities as the source of intermittency. Their first suggested source is a central movement planner that utilizes submovements to generate plans for complex movements consisting of building-block type simpler movements. Their second suggested source is noise being interjected on top of a continuous (or intermittent) plan along the neuromuscular circuitry. Doeringer and Hogan do not arrive at a final conclusion about the source of intermittency. They do however state that interpreting peaks in tangential speed profiles as incomplete blending of submovements would lead to a conclusion favoring the central planner option for being responsible for intermittency. Same conclusion was also reached by Dipietro et al. [6].

We show that movement intermittency increases in the distal direction along the human arm. We believe that this trend is an indication that intermittency is due to neuromuscular noise and not due to an originally intermittent movement plan used by the central nervous system. In our work, five participants completed manual circular tracking tasks in both vertical and horizontal planes, as the shoulder, elbow, wrist and fingertip trajectories were captured by a Vicon motion capture system that is capable of accurately tracking and reconstructing 3D positions of markers. This motion capture system offers a number of key features. First, we are able to record completely natural human movements with minimal interference to the participant. Other approaches (e.g. splints or arm rests attached to the arm and equipped with sensors) can add inertial or friction disturbances to the participants' arm movements. Second, we are able to record multiple joints or points on the limb simultaneously. This feature enables us to compare movement intermittency at various locations on the limb. Sternad and Schaal recognized the importance of acquiring movement data simultaneously from multiple points on the limb. They implemented this technique in their work on segmentation of end point trajectories [7]. They showed that such segmentation was not necessarily due to a segmented control plan, but may be explained by a con-

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tinuous sinusoidal control of the joints which transform into rhythmic endpoint trajectories that appear to be segmented due to the nonlinear forward kinematics of the system.

Using rhythmic movements only, Nagasaki [8] showed that speed profile of the movements transformed from being asymmetrical to symmetrical as the frequency of the movement increased. Especially over 4.3 Hz, speed profiles became highly symmetrical. He listed changing muscular dynamics (stiffer muscles at higher speeds), as reported by Wann et al. [9], as a potential reason for observed transition to symmetric profiles. It should be noted that, contrary to these two studies considering the effect of muscular dynamics on end point movements, Doeringer and Hogan [5] specifically excluded biomechanics as a source of intermittency in their consideration based on their working definition of intermittency.

To explore the source of intermittency, we asked participants to make circular arm movements at five different speed conditions. Movement intermittency of markers placed along the arm was calculated based on the tangential speed profile of the marker, and movement intermittency was quantified as the number of peaks observed in the speed profile. Results show that intermittency at the fingertip is greater than intermittency at the wrist and the elbow, and intermittency at the wrist is greater than that at the elbow. This trend indicates that noise is a likely source of intermittency, since the intermittency would be amplified due to additional noise being interjected through the limb 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 limb.

The paper is structured as follows: Section II details the experimental protocol and participants, motion capture system and data preprocessing procedure, intermittency metric calculation and statistical analysis methods. Section III presents the effects of speed and orientation conditions on intermittency as well as the change observed in intermittency with respect to position of the markers on the arm. Subsequently, results are discussed in comparison to the related findings in the literature and implications for various related research tracks are summarized.

II. METHODS

A. Participants

A total of five participants completed the experiment in the Computer Graphics and Interactive Media Lab of University of Houston. All participants provided informed consent which was approved by the Institutional Review Boards of Rice University and University of Houston. Participant ages were 25–28, one was female, one was left-handed and all completed the experiment with their dominant arm and hand. All participants had normal or corrected-to-normal vision and none had any movement disorders affecting the dominant hand. Three participants completed the horizontal orientation session first (explained in the following section).

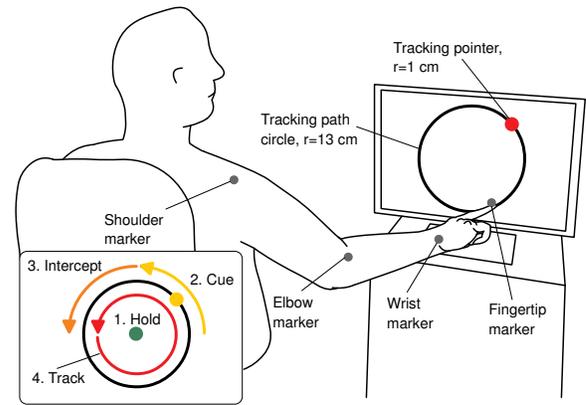


Fig. 1. An illustration of a participant in the experimental setting with attached motion capture markers. Inset at bottom left: The trajectory that the tracking pointer follows as a trial progresses through the four phases: (1) pointer at the center during the hold phase, (2-4) pointer changing colors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

B. Experiment Protocol

Participants were asked to wear a jacket on which motion capture markers were attached on the bony parts of the limb on the shoulder, elbow and wrist joints and a fourth one on the nail of the index finger. A lightweight rod with two markers on its ends was attached on the back side of the hand to capture wrist rotations (pronation/supination), though data from the latter two markers were not used in this study. Participants were seated at an LCD computer screen which was in reach of the index finger. An illustration of a participant with attached motion capture markers is given in Fig. 1. Participants were informed that once the position of their chair and the position of the screen were adjusted, they should not be moved. Participants were also told to keep their shoulder as fixed as possible throughout the experiment. Shoulder movements that could have still occurred was not a concern for the reported results, for either of the coupled and decoupled data sets (see Section II-D).

The experiment consisted of two sessions of 25 trials each. During one of the sessions the computer screen was in a normal (upright) position (*vertical* tracking plane/orientation). During the other session, it was lying on the table facing up such that participants looked down at the screen from a standing posture (*horizontal* tracking plane/orientation). The order of presentation of these cases to each participant was determined randomly, and all participants experienced each orientation of the screen.

Regardless of the screen's orientation, during the trials, participants were asked to track the pointer that was moving on a white circular path (always visible) on a black background with the tip of the index finger (see Fig. 1) as accurately and as smoothly as possible, in order to minimize intermittency. Participants were asked to track the pointer without touching the screen, positioning the tip of their index finger within around 1 cm of the surface. The speed of the pointer to be tracked changed randomly among trials, but it was constant within a single trial. Tracking speed displayed

by the pointer formed the second within-subjects factor in the experiment, and we tested five levels: 2.5 cm/s, 3.75 cm/s, 5 cm/s, 12.5 cm/s and 25 cm/s (given as the tangential speed on the perimeter of the 26 cm-diameter tracking circle/path).

Each trial consisted of four phases as schematically shown in the inset on the bottom left on Fig. 1. In the *hold* phase, a green pointer with approximately 2 cm diameter (all pointers had the same diameter) at the center of the screen was displayed. Participants were asked to point to the center of the green dot as soon as they saw it and wait there until the next phase. The time period for this phase was 3 seconds. In the *cue* phase, a yellow pointer appeared at the 3 o'clock location on the white circular track. This pointer moved from 3 o'clock to 12 o'clock (counterclockwise-ccw) with a certain constant speed, to give the participant a feeling of the speed that they would need to track by pointing at it with their index fingertip. During this phase, participants were asked to keep their position at the center of the green pointer, and just observe the movement of the yellow pointer. In the *intercept* phase, the yellow pointer changed its color to orange as it passed through 12 o'clock. It maintained its constant speed and moved towards 9 o'clock (again ccw). During this quarter circle movement, participants were required to catch the pointer by pointing with their index finger and to start tracking it. In the *track* phase, as the pointer passed through the 9 o'clock position, its color became red, but its speed remained the same. Participants were asked to track the pointer until it made a full circle in the ccw direction. Data from the tracking phase of each trial were analyzed. The duration of last three phases varied according to the tracking speed for that particular trial. After completing the four phases, the screen went blank for a very short period, and then the next trial began with the hold phase. The visual interface design was adapted from Pasalar et al. [10] where they analyzed the changes in the submovement properties for varying tracking speeds and force fields with a planar manipulandum.

After completing one session with 25 trials, participants were asked to rest for at least 10 minutes before going on to their second session (the other orientation condition). Participants were asked to inform the experimenters as soon as they felt their arm was fatigued, and the experiment was paused between trials until the participant felt comfortable to continue, to exclude potential confounding effects of fatigue on intermittency. There were typically three to four such breaks within one session. After completing the experiment, participants completed a short questionnaire. A total of 250 trials were recorded corresponding to 5 participants \times 5 speed levels \times 5 trials for each speed level \times 2 orientation levels.

C. Motion Capture and Data Preprocessing

Motion data were acquired with a Vicon motion capture system with ten high resolution MX 40 cameras used for marker motion recording (see Fig. 2), two MX Giganet controlling hardware modules for handling the communication, synchronization and control of data flow between cameras



Fig. 2. Vicon motion capture system used in the study to capture the trajectories of the markers depicted in Fig. 1.

and the PC terminal, and Vicon NEXUS 1.3 data processing software for controlling the MX Giganets, enabling real-time capture feedback and data post-processing such as data cleaning and data labeling. The markers used for the experiment were of 5 mm diameter. All three Cartesian coordinates of shoulder, elbow, wrist and fingertip markers were recorded in mm at a sampling rate of 50 Hz.

Captured data for each trial were first visually checked and manually cleaned in the NEXUS software. Then raw data were converted into ascii format text files with marker coordinates in mm. These files were imported into MATLAB and the extraneous portions of data at the beginning and the end of each trial that did not belong to any phase of the trials were removed. A gap-filling method using cubic splines was applied for the cases where a small portion of data for one or more markers were missing within a trial, primarily due to occlusions. Only 16 trials out of 250 required such interpolation of data and 15 of these trials ended up being included in the data analysis. Among these 15 files, the average ratio of interpolated data points to total data points was 2.6% (2 of them were about 17%, the other 13 were less than 7%). The trials were further truncated to extract only the circular tracking phase of each trial. A total of 12 trials out of 250 were determined to be incomplete due to either the recording or the participant ending the trial before the full circle was completed, and these trials were removed from the data set for analysis. Incomplete trials were not specific to a participant, speed level or orientation.

D. Coupled/Decoupled Data Sets and Intermittency Metric

We generated two versions of the data set consisting of 238 trials: an original set with no further processing and 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 position. The purpose of the decoupling was to be able to assess intermittency of individual isolated joint movements. Without decoupling, increase of intermittency in distal direction would be a trivial result, since noise or intermittency in the proximal joint movements would cumulatively add to the intermittency in the distal joint

movements. After decoupling, we were able to disregard the kinematic accumulation of noise and instead observe any accumulation of noise in transmission of the movement plan or neuromuscular actuation signals. Note that for the original data set, the nomenclature shoulder, elbow, wrist and fingertip actually correspond to the cartesian coordinates of the respective markers, whereas for the decoupled data set, fingertip data now reports (fingertip–wrist), which can be regarded as the movement of the fingertip with respect to the wrist and not to the fixed coordinate system. This effectively becomes information about wrist joint movement as opposed to a tracked single point in the task space. Although after the transformation fingertip data now contains wrist joint information, the same designation of “fingertip” will be used for this data component.

Both the original and the decoupled 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 difference Euler algorithm. The Euclidean norm of three components of the velocity vector for each marker was used to obtain the tangential speed profile. As a measure of intermittency, we used the number of peaks in the tangential speed profile. This metric is one of the five smoothness metrics used by Rohrer et al. [11] to quantify and analyze submovement blending observed in stroke patients’ movements during the motor function recovery period. Kahn et al. [12] also used the number of peaks metric in a stroke rehabilitation related study. We use a definition for the intermittency metric that is similar to one used by Kahn et al. Specifically, among the local minima and maxima within the tangential speed profile, we use a criterion of having an increase of at least 10% of the global maximum in the profile between a local minimum and the following local maximum to be included into the count of peaks in the profile. The global maximum value was restricted to less than three times the mean speed within the trial. The metric takes integer values since it is a count of peaks, and a higher value corresponds to higher intermittency.

E. Statistical Analysis

To justify applicability of parametric statistical tests, we first conducted a nonparametric Kolmogorov-Smirnov test and compared each data subset for a specific joint and speed level with a normal distribution of equivalent mean and variance. Among the thirty such data sets (five speed levels, three joints and coupled/decoupled data sets), each of which included a minimum of 45 data points, only four data sets had a distribution significantly different from a normal distribution at alpha level of 0.05. Three of these data sets belonged to the fastest speed condition, for which the resolution of the intermittency metric was low due to only a few number of peaks observed in the speed profiles. Nevertheless, we conclude that it is appropriate to use parametric tests for our results, a majority of which failed to show significant differences when compared to an equivalent normal distribution.

Relating to the main question of the study, to compare the

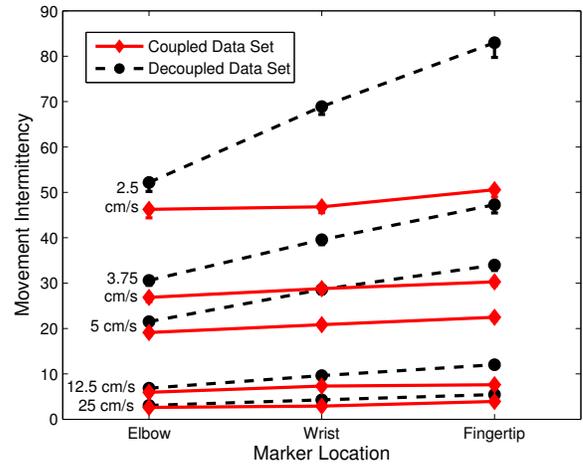


Fig. 3. The mean and standard errors of movement intermittency at the corresponding markers for varying speed levels are plotted to illustrate the increasing intermittency trend in distal direction. The trend is more pronounced in the decoupled data set. Based on the results of the paired sample t-test, 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.

movement intermittency of elbow to wrist, elbow to fingertip and fingertip to wrist, we used a standard two-tailed paired-sample t-test, where all 238 trials were utilized after pairing the values of intermittency for the two markers of interest within the same trial. We conducted the test on both the original and the decoupled data set.

As for the effects of speed and orientation conditions, our experiment has two within-subjects factors and no between-subjects factors. To increase the robustness of the data and conduct a balanced analysis despite the excluded incomplete trials, we first averaged the intermittency values corresponding to one participant, one speed condition and one orientation condition. This averaging process was checked and verified to include at least four trials and ideally five trials for each case. Then we conducted a multivariate analysis of variance (MANOVA) for determining the main and interaction effects of orientation and speed factors on movement intermittency, as well as for pairwise comparisons of the individual speed levels.

III. RESULTS

In section III-A, we show that intermittency in arm movements during a circular manual tracking task significantly increases as the movement propagates along muscles and joints in the distal direction, regardless of the data set being used (coupled or decoupled). In section III-B, we show that the main effect of movement speed on intermittency is statistically significant, while the orientation of the tracking plane does not have a significant main effect on intermittency. The data fails to show significance for interaction effect of speed and orientation, meaning that doing the tracking task in different planes would not significantly effect the intermittency characteristic for varying speed levels differently. We report that the endpoint speed levels used in

this study induced significantly different intermittency values observed at the endpoint by comparing the mean differences between individual speed levels. This implies that movement intermittency is ever present within a wide range of speeds and varies proportionally yet nonlinearly with increasing or decreasing speed values.

A. Intermittency Increases in Distal Direction

Results of the paired-sample t-test are given in Fig. 3. In this figure, the mean and standard errors of movement intermittency for all trials corresponding to one of the markers (elbow, wrist or fingertip) for varying speed levels are plotted. With respect to the coupled (original) data set results, a significant difference between means exists for elbow vs. wrist [$t(237) = -5.03, p < 0.001$] and elbow vs. fingertip [$t(237) = -10.04, p < 0.001$], in both cases intermittency for elbow movements is significantly less than intermittency at the wrist and fingertip. Data further indicate significant differences between intermittency at the wrist and fingertip as well [$t(237) = -7.46, p < 0.001$], intermittency at wrist being less than intermittency at fingertip. Similar significant results for the intermittency of elbow vs. wrist [$t(237) = -13.30, p < 0.001$], elbow vs. fingertip [$t(237) = -14.30, p < 0.001$] and wrist vs. fingertip [$t(237) = -9.24, p < 0.001$] are obtained using the decoupled data set, again former point being more intermittent in each pair. In summary, all six pairwise comparisons of movement intermittency at different points on the arm resulted with significantly higher intermittency for the more distal point.

B. Speed and Orientation Effects on Intermittency

Results of the MANOVA analysis for the fingertip (endpoint) marker using the decoupled data is summarized in Fig. 4. As expected, movement intermittency decreases for higher speed levels, and the main effect of speed on intermittency is found to be statistically significant [$F(4, 1) = 2037, p < 0.05$]. Data for the main effect of tracking plane orientation on intermittency failed to show significance [$F(1, 4) = 0.64, p = 0.47$], which is apparent in the very close lines for the different orientation conditions in Fig. 4. Data for the interaction effect of speed by orientation on the movement intermittency also failed to show significance [$F(4, 1) = 0.38, p = 0.82$], as depicted by the mostly parallel lines in Fig. 4. Results obtained using the coupled data set that are not reported here were mostly similar. Only difference was that the main effect of orientation on intermittency was found out to be significant [$F(1, 4) = 13.71, p < 0.05$] for the coupled data set. 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.

A pairwise comparison of five speed levels using the decoupled data set with the end point marker showed that the intermittency at fingertip marker was significantly different at the five speed conditions ($p < 0.05$). We obtained similar results for the wrist and elbow markers using either of the

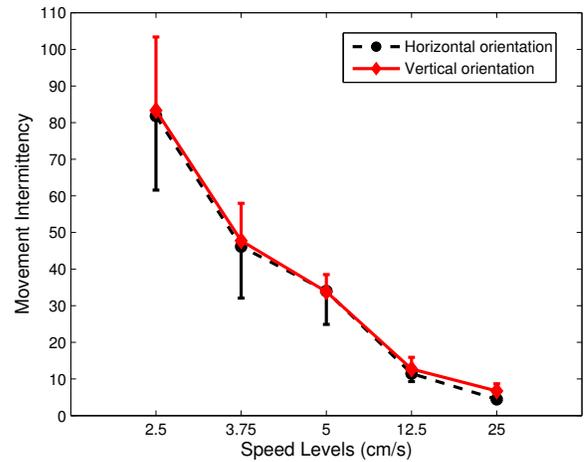


Fig. 4. Results of the MANOVA analysis for the fingertip (endpoint) marker using the decoupled data. Plotted are mean values with error bars representing standard deviation. Movement intermittency decreases for higher speed levels, and the main effect of speed on intermittency is found to be statistically significant [$F(4, 1) = 2037, p < 0.05$]. The main effect of tracking plane orientation on intermittency failed to show significance [$F(1, 4) = 0.64, p = 0.47$], which is apparent in the very close lines for the different orientation conditions. Data for the interaction effect of speed by orientation on the movement intermittency also failed to show significance [$F(4, 1) = 0.38, p = 0.82$], as depicted by the mostly parallel lines.

data sets. Therefore the speed levels used in the study are spaced apart enough to induce significantly different movement intermittency. It can be observed in Fig. 4 that although there is a monotonically decreasing trend in movement intermittency for increasing movement speeds, the differential change in intermittency between consecutive speed levels is much higher at the slow end of the speed scale. This is in agreement with the qualitative results and observations reported in the literature [3], [5].

IV. DISCUSSION

The fact that significant increases in movement intermittency are observed for the speed profiles of points located along the distal direction on the arm supports a neuromuscular noise alternative against a discrete central movement planner hypothesis as an explanation for the movement intermittency observed especially in slow human movements. Although there is strong evidence for the existence of submovements in the literature [3], [10], [11], we report here that submovements as generated by a central planner are not necessarily responsible for the intermittency of movements. Our results are in agreement with those reported by Nagasaki [8] and Wann et al. [9], although we do not explicitly propose a change in muscular properties as the source of movement intermittency.

We show that orientation of the plane in which the endpoint movement lies is not a significant factor in movement intermittency. Orientation does not demonstrate a significant interaction effect by speed conditions on intermittency, either. This result can help researchers simplify their experiment design for movement intermittency or smoothness related work.

Our finding that movement intermittency increases significantly with decreasing movement speed is in agreement with work by Dipietro et al. [6]. We present a systematic characterization of movement intermittency at different joints of the arm. Although separate studies in the literature concerning individual joints [5], [13] together implied an increased movement intermittency in distal joints, we provide a comparison of movement intermittency in several joints under simultaneous recording, hence equivalent temporal and task conditions.

We believe that 3D motion tracking offers great opportunities for the study of human motor control, as reported also in [7], especially in identifying and clarifying interesting manifestations of the motor control system which underlies its great flexibility, dexterity and adaptability [2]. The ability to simultaneously track multiple points in 3D was a key feature of the motion tracking system that we used to explore the source of movement intermittency.

One application area for our results would be better design of robotic rehabilitation protocols. Movements of stroke patients are highly intermittent and the intermittency decreases as the patient relearns to move. Due to this fact, movement smoothness is widely used as an objective metric to quantify motor function recovery in stroke patients [11], [14]. In a study that compared benefits of first distal robotic therapy and then proximal therapy vs. the therapy scheme with the alternative order, Krebs et al. [15] reported that although the overall outcomes were very similar for both groups of patients, the skill transfer effect was higher in the group that underwent the more distal therapy first. We believe that this observation can be explained within the light of our results. Trying to generate a smooth distal endpoint trajectory, even if the proximal joints were restrained, would imply more intense exercise for the patient than an exercise focusing on a more proximal joint, since intermittency is not due to simple accumulation in kinematic variables, but due to an accumulation in the neuromuscular circuitry. Testing of the patient with a proximal joint task after distal joint exercise is then similar to increasing the tolerance band in the task. We plan to extend our work to test our hypothesis using additional metrics for movement intermittency, such as mean squared jerk and others reported by Rohrer et al. [11].

V. CONCLUSION

We report the results of our experimental study aiming to shed light on the origins of movement intermittency in human motor actions. Data were collected during a manual circle tracking task completed by five participants at various constant speeds. Through use of a 3D motion capture system and simultaneous recording of shoulder, elbow, wrist and fingertip trajectories, we show that intermittency is significantly higher in the more distal joints of the arm. This result supports a neuromuscular noise model as the source of intermittency as opposed to a central movement planner model that generates intermittent plans. We also show that speed is a significant factor on movement intermittency, while orientation of the endpoint task plane is not. Our

results have implications for fundamental research in motor control and motor planning as well as applications in robotic rehabilitation, motor skill learning and motion control in humanoid robots.

VI. ACKNOWLEDGMENTS

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