Muscle Synergy Analysis in Dart Throwing*

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***Abstract*— This study aims to analyze muscle synergies in darts throwing movement to clarify how the central nervous system (CNS) controls muscle activation to produce complicated motion. Activities of 10 different muscles on upper limb were recorded through surface electromyography (EMG) electrodes from four participants with less experience of dart throwing. Subsequently, non-negative matrix factorization (NNMF) was applied to the collected EMG signals for muscle synergy analysis. Results showed that three muscle synergies could explain sufficiently the observed EMG data, with determination coefficient $r^2 = 0.91 \pm 0.02$ across four subjects. However, it was found that there was significant difference in terms of patterns of both muscle synergies and activation coefficients between participants, which might reflect different neuromuscular control strategies in dart throwing.**

I. Introduction

Throwing is an important movement of human in various circumstances. Understanding underlying motor mechanisms and neuromuscular functions of throwing motion enables us to apply the knowledge to a wide range of fields such as sports science. We have investigated dart throwing, an accuracy-dominated movement, which requires sophisticated combination of several mechanical and neuromuscular factors in finger, wrist, elbow and shoulder joints, to comprehend how different muscles on upper limb synchronously activated together to produce the movement.

There is a hypothesis that the central nervous system (CNS) simplifies the degree of freedom by recruiting a small number of group of muscles, or reducing the number of controlled variables to produce movements, and this concept is known as "synergy hypothesis" proposed by Bernstein [1]. Several studies investigated muscle synergies in many human movements such as walking [2], cycling [3], standing-up [4] or fast-reaching [5]. These movements were suggested to be produced by combination of a group of muscles activated together. However, in the case of dart throwing movement, which is produced by activation of several muscles on different segments of the upper limb simultaneously, muscles synergy analysis is less investigated. Therefore, this study aims to clarify whether the CNS can produce the darts throwing movement by controlling just a few variables. If it is true, it is a supplementary evidence to support the muscle synergy hypothesis. Besides, unlike the above-mentioned behaviors, accuracy is required for the dart throwing. Strategies in terms of kinematics [6] would be different, so that muscle synergy patterns might be different between the subjects. Accordingly, it is feasible to evaluate the quality of a throwing through muscle synergies, as proposed similarly in clinical evaluation [7]. For instances, co-activation phenomenon of agonist and antagonist muscles, *Triceps* and *Biceps*, was confirmed in beginners [8] and it has a negative effect for a good throwing.

In our previous studies [8][9], activities of four muscles on fingers and upper arm were examined. However, the number of muscles could not explain the flexion and extension of the wrist and shoulder adequately, and it seems not to be enough to muscle synergy analysis. Therefore, in this work, we recorded surface EMG signals of 10 different muscles on the shoulder, upper arm and forearm to enrich the investigation.

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II. Methods

A. Experiment

Subjects: Four healthy young males (A, B, C and D), 24.25 ± 0.5 years old, 167.93 ± 7.96 cm tall, participated in the experiment. Three of them (A, B and C) were right-handed and D was left-handed. All participants were novices in dart throwing but B had more experience. We chose metal hard darts for the experiment.

Materials and data collection: Since trajectory of the projectile is only affected by the gravity in the vertical plane (acceleration is zero in the horizontal plane, with ignoring the air resistance and any rotation [6][10]), we assumed that a throwing movement was performed in a 2-dimensional plane. Therefore, in our study, subjects were asked to perform the task with a stance where the trunk, upper and lower limbs were almost moved in the same plane, facing to the dartboard.

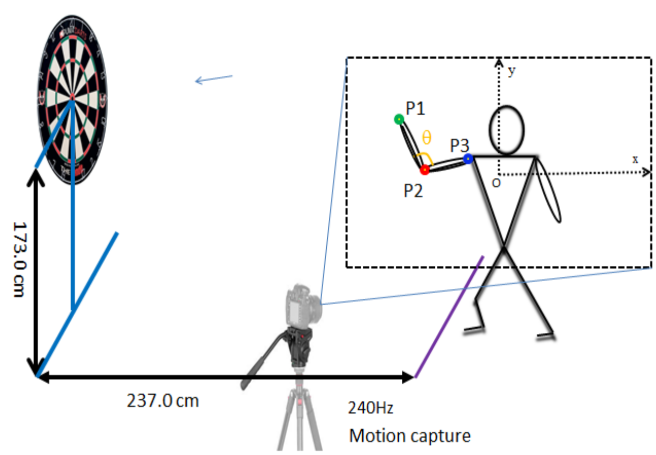

Figure 1. Motion capture system in the experiment. The dash-rectangular depicts a 2-D space for measuring kinematic data, with the coordinate axes (in pixel) and the origin (O), which will be processed and analyzed in Kinova software.

A high-speed camera (Casio EXILIM EX-100F, 240 Hz) was put perpendicularly with the movement plane of subjects to capture a throw. Three markers were put on the wrist, elbow and shoulder for measuring the elbow angle, the most vital joint in darts throwing motion (Figure 1). The motion capture data were accessed through Kinova software (0.8.24 version) after the experiment. The release timing (RT) was detected by a custom-made digital circuit with an LED by adhering 2 thin pieces of metal tapes (0.065 mm) on the thumb and index fingers. The ON/OFF signal was then fed into an A/D board for synchronization with EMG signals. Trajectories of the wrist, elbow and shoulder were smoothed by moving average with a window size (7 samples).

In EMG analysis, 10 muscle activities were recorded by surface EMG electrodes: *Flexor pollicis longus* (FP), *Extensor indicis* (EI), *Extensor carpi radialis* (ER), *Flexor carpi radialis* (FR), *Flexor carpi ulnaris* (FU), *Brachioradialis* (BR), *Biceps brachii* (BB), *Triceps brachii long head* (TB), *Anterior Deltoid* (AD) and *Posterior Deltoid* (PD). Since dart throwing requires a sophisticated coordination of muscle activations on different segments of the upper limb, we selected the muscles which functionally involves to the thumb and index movements (FP and EI); wrist extension and flexion (ER, FR and FU); driving the forearm forwards (BR, BB and TB) and the shoulder movement (AD and PD). Before attaching the electrodes, skin was shaved and cleaned by alcohol to reduce impedance. Since dart throwing is an intensive movement, adhesive tapes were carefully attached to fix electrode positions during throwing. EMG data were recorded and amplified by a multi-telemeter system (Nihon-kohden, Japan) and then send to the A/D board.

Procedure: Before the experiment, subjects were asked to practice throwing in 10 minutes to get accustomed to the dart, standing position (237 cm apart from the board) and especially the metal tapes. Each subject performed 60 dart throws, divided into two sessions, aiming at the bull-eyes of dartboard

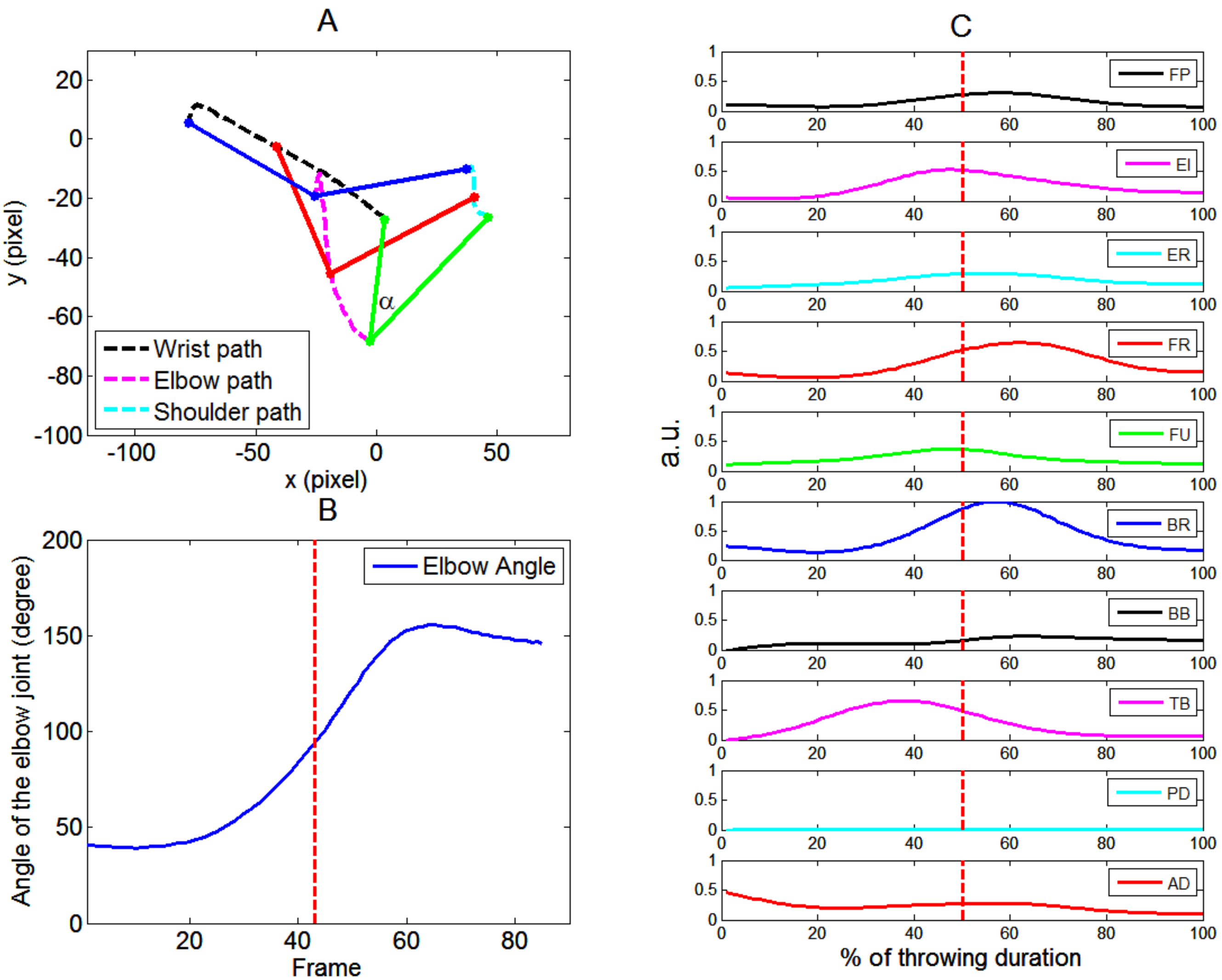

Figure 2 An example of kinematics data and corresponding EMG signals synchronized by the release timg (RT) of a throw during the *throwing duration* (THD). **A**. Trajectory of the arm in the THD. The black, matengan and cygan dashed lines describe throwing paths (from the right to the left) of the wrist, elbow and shoulder in Kinova software, respectively (see Figure 1). The 2 bold lines in the same color preresent the upper arm and forearm while throwing, with the green lines depict the arm at the starting point of the THD, the red lines depict at the RT and the blue ones depict at the ending point. The RT point divided the THD into 2 periods equally. **B**. Elbow angle (α in Figure 2A) of the throw in the THD. The dashed red line represents the RT (at the middle of the THD), a video frame = 4.17 miliseconds (the camera with 240Hz). **C**. Corresponding EMG signals of the 10 muscles recorded in the THD after timing and amplitude normalization. The dashed red lines in all channels represent the RT point, which was synchrnozied to the RT point in the kinematic data in Figure 2B.

(173 cm in height). Each session consisted of ten 3-throw sets. To measure throwing accuracy of a subject, we attached a piece of paper with a printed image of dartboard (with the same size) over the actual dartboard. The paper was attached in a way that the bull-eyes, numbers, double and triple rings of the image were exactly overlapped the respective ones on the dartboard, which means a dart's final positions on the image and the dartboard were the same. After a throwing set, we rapidly took out darts and marked corresponding positions on the paper, which took about 20 seconds and then ask the subject to perform the next set. When the subject finished the two sessions, the paper with 60 marked points was taken out for measuring errors (distances) correlated to the bull-eyes. Between the two sessions, there was a 5-minute short break.

Throwing duration: for easy of explanation, we divided a throwing movement into 3 phases: *take back*, *throwing* (i.e., duration starting from the smallest elbow angle to the release timing), and *finish* (i.e., after the release timing). Since subjects have their own strategies and postures in take back phase, we focused on EMG data in a period during throwing and finish phase for investigating, which was defined as *throwing duration* (THD) in our work. The starting point of the duration was the smallest angle of the elbow joint with the corresponding amplitude of TB, the main muscle produced force to drive forearm forwards to throw, started to activate. The ending point of a throwing path was chosen so that the RT point was put in the middle of the path (Figure 2A and 2B).

B. *Muscle synergies*

Data processing: Raw EMG data were recorded at 1024 Hz, full-wave rectified, applied a zero lag low-pass filter (10 Hz, Butterworth filter, 2nd order). In each throwing, only EMG data corresponded to the THD in kinematics data was accessed by the synchronized signal (ON/OFF signal). For timing normalization across trials, an envelope of EMG data in the THD for synergy analysis was created by resampling at 1% of the THD to obtain 100 samples. The amplitudes in an envelope were normalized by the maximum value in all muscles to evaluate how strong activations between the selected muscles while throwing were (Figure 2C). Then 100-sample envelopes of all total 60 throws in each subject were concatenated for muscle synergy analysis afterwards.

Muscle synergies: In our work, time-invariant muscle synergies, in which all muscles activate synchronously, were examined by decomposing the observed EMG signals. Muscle activation patterns were assumed to result from linear summation of spatiotemporal patterns by applying Non-negative Matrix Factorization (NNMF) [11] with the following equation:

$$M \cong \sum_{i=1}^{N} W_i \times c_i \qquad (1)$$

M was observed EMG data of concatenating all 60 trials. Thus M resulted in 10-by-6000 matrix, which represents patterns of 10 muscle activities, with 60×100 samples. W represents muscle synergies that define spatial patterns whereas C represents time-series activation coefficients. We evaluated how much the reconstructed patterns could explain the observed data by determination coefficient r^2. With all subjects, we varied the number of synergies (N) from 1 to 7 and then selected the smallest number of synergies with the threshold that $r^2 > 90\%$ [4].

III. Results

A. *The number of synergies*

Figure 3 shows the relationship between determination coefficient and the number of synergies. Applying the above criteria, we chose the number of synergies $N = 3$, where the $r^2 = 0.91 \pm 0.02$ in all subjects.

B. *Synergy activation and activation coefficients*

Figure 4 shows the three muscle synergies (S1, S2 and S3) extracted from the 10 muscles of each participant. Each bar chart represents activation levels of 10 muscles within each synergy during the throwing period.

Figure 5 illustrates the average of activation coefficients, time-series of synergies within an activation envelope, with total 60 throws of all participants. The dashed, red line is the RT, at the 50th sample (in the middle of the envelope). The blue, green and red bold lines represent the first, second and third activation coefficients, respectively.

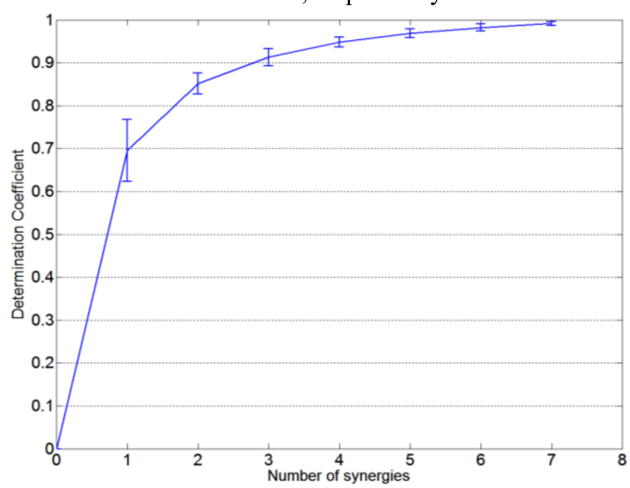

Figure 3 The relationship between the number of synergies and determination coefficient after apply synergy analysis.

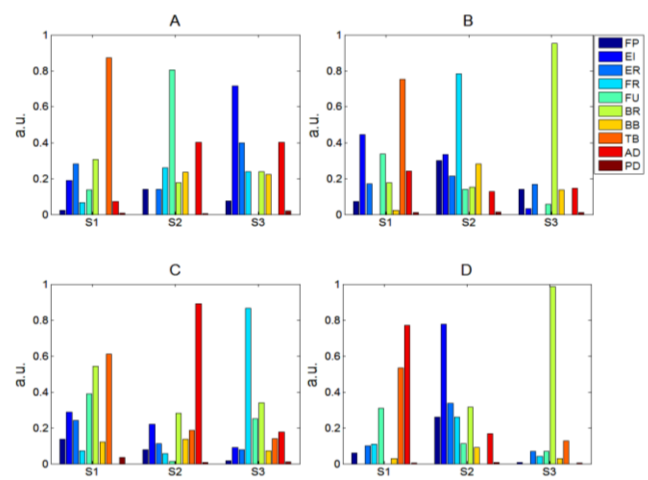

Figure 4 Muscle synergies of all participants

IV. Discussion

We investigated muscle synergies in dart throwing motion to clarify how muscles activate together to produce the throw. Activities of 10 different muscles on the shoulder, upper arm and forearm were recorded through surface EMG. The result showed that 3 synergies can explain the observed muscular patterns sufficiently (r^2 = 0.91 ± 0.02), contributing to the hypothesis beside a wide range of human movements ([12]).

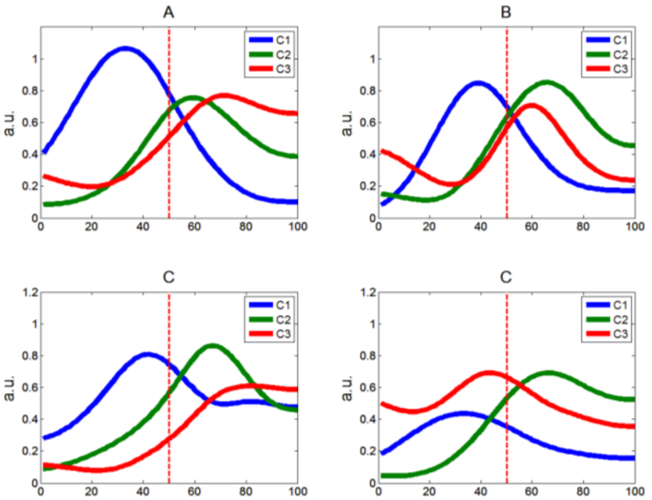

Figure 5 Activation coefficents of all participants.

In terms of synergy activation coefficients, the first and second profiles (C1 and C2) were similar across the participants whereas the last ones (C3) might be subject-specific. Namely, the first synergy activated and got to the peak before the RT while the second synergy activated after the RT. The third time-course activations among the subjects were different, i.e. with subject A and C, the third synergy activated immediately after the second synergy, while significant variability was observed in subject B and D (Figure 5). The variability witnessed might be caused by different postures or strategies, we will discuss later.

Regarding synergies, under a viewpoint of anatomy, in general, the first synergy (S1) activated the TB, the main muscle which produces force for elbow extension, before the RT. However, in subject D, there was also a large activation level of AD corresponding to intensive shoulder movement, which means the subject utilized the muscle of shoulder to support the upper arm to drive the arm forwards.

In the second synergies (S2) of subject A and B, there were dominated activation levels in FR and FU, respectively, which both were activated for wrist flexion. The result implies that the subjects flexed the wrist after opening fingers to release a dart. Meanwhile, large activation level of AD was observed in the S2 of subject C, corresponding to shoulder flexion after the RT. Subject D extended the index finger after release, corresponding to large activation level of EI. Therefore, after the RT, subjects utilized neuromuscular control strategies differently, with dominated activation of different muscles for wrist flexion (FR or FE), shoulder flexion (AD) or index extension (EI).

In the last synergy (S3), with large activations of EI, subject A extended index immediately after wrist flexion at the end of the throwing period. Similarly, subject C flexed the wrist after shoulder flexion (large activation level of FR in the S3). Meanwhile, overwhelming activation of BR was found in the synergy S3 of subject A and D. Though one can argue that forearm pronation or supination (functions of BR) of the two subjects were intensive during throwing, the corresponding activation coefficients (C3) were significant variability and unfamiliar, as we mentioned before, likely due to the following reasons and drawbacks. Firstly, all subjects were beginners performing with free postures, activities of trunk and lower extremities were ignored, which might lead to the variability. Besides, amplitude normalization in this work should be re-examined. Therefore, at the moment, we could not conclude about the third synergy in subject B and D. However, at least we indicated that muscle synergies can explain sufficiently the observed EMGs (r^2 = 0.91 ± 0.02) in dart throwing movement. Also, beginners seemed to use different neuromuscular strategies to get the task.

In future works, we will analyze muscles from the trunk and lower extremities. Moreover, it is important to analyze neuromuscular activities of experts in dart throwing to clarify differences from novices for training and whether muscle synergistic patterns of them are similar.

Acknowledgment

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