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Comparison of experts and non-experts in throwing darts based on optimization criteria

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Abstract— **Acquiring skillful movements of experts is a difficult task in many fields. Since non-experts often fail to find out how to improve their skill, it is desirable to find quantitative indices of skillful movements that clarify the difference between experts and non-experts. If we find quantitative indices, we can develop an adaptive training system using the indices.**

In this study, we quantitatively compare dart-throwing movements between experts and non-experts based on their scores, motions, and EMG signals. First, we show that the variance of upper-limb motion trajectories of the experts is significantly smaller than that of the non-experts. Then, we show that the displacement and the variance of the shoulder of the experts are also significantly smaller than those of the non-experts. The final result is the highlight of this study. We investigated their upper-limb motions from the viewpoint of trajectory optimization. In this study, we focus on two popular optimization criteria, i.e., sum of squared jerk over a trajectory and sum of squared joint-torque change over a trajectory. We present that the sum of squared joint torques of the subjects was negatively correlated with their scores ($p < 0.05$), whereas the other criteria were not.

I. INTRODUCTION

Recently, throwing motions of experts and non-experts have been compared based on biological information such as motion and electromyographic (EMG) signals [1]. For example, Proximal-to-Distal segmental Sequencing (PDS) is found in both joint-angular velocities and EMG signals [2]. PDS indicates such a phenomenon that limb motions are described by successive transitions of a joint having the highest velocity and the beginning of the EMG activation of a muscle from the body trunk to the periphery. Finding PDS is attractive because it is strongly related to synergetic motor control.

In this paper, we compare the dart-throwing between experts and non-experts based on their scores, motions, and EMG signals. We chose dart throwing because it is essentially different from ball throwing in previous studies as follows. Throwing darts is simple because it is usually performed by fixing the body trunk and is primarily driven by an upper-limb. The weight of a dart is much lighter than a ball, and acceleration required in the hand tip for throwing a dart is much smaller than that of a ball. The possibility of muscle fatigue is much lower in throwing darts. Hence, the influence on the muscle activity caused by fatigue should be much smaller in throwing darts. In contrast to the previous studies, we examine the difference between experts and non-experts from the viewpoint of optimal motor control.

TABLE I

BODY PARAMETERS OF ALL SUBJECTS

Subjects	Weight [kg]	Height [cm]
A	80	183
B	65	172
C	61	172
D	67	176
E	67	182
F	80	171

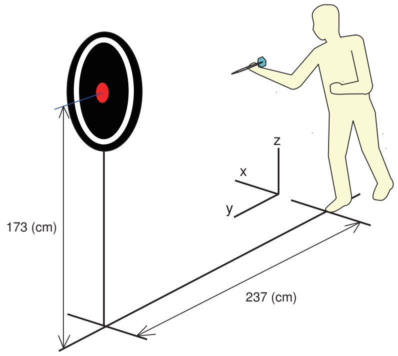

Fig. 1. Overview of experimental set up of throwing darts

The organization of this paper is as follows. Section II describes our experimental settings and data analysis with optimization criteria for motor control. Then section III presents results and related discussions. Finally, section IV concludes this paper and describes some future work.

II. METHODS

A. Subjects

Six healthy subjects (adult males, age 25 ± 1 years) participated in this experiment. Their body parameters are shown in TABLE I. We classified them into two groups based on their darts scores.

B. Experimental setup and data preprocessing

The task was soft-tip darts. The goal of this task was to shoot a bull's eye on a dart board. The setting of the dart board and the standing location of the subjects followed the official rules of the World Darts Federation (WDF) as shown in Fig. 1. Scores of bull's eye, inner single ring, triple ring, outer single ring and double ring are 5, 4, 3, 2 and 1 point, respectively. Subjects were instructed to shoot for the bull's eye as much as possible with their preferred rhythm. Before the actual task, the subjects were asked to throw darts 30

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times. The actual task consisted of 12 trials. In one trial, the subjects initially held four darts with their right hand, and threw them one by one.

We used PC DARTS (Epoch CO., LTD) consisting of a board with a USB connection to a PC, and darts with a soft tip. The scores were automatically calculated by the PC DARTS. We used a MAC3D System (Motion Analysis Corp.) for measuring upper-limb motion and EMG signals simultaneously. Markers for optical motion measurement were attached to each subject's upper-limb (shoulder, elbow, and hand) according to the Helen Hayes Marker set. EMG signals were recorded by compact-electromyograph BA1104 (Digitex Laboratory) with active-type electrodes and telemeter unit TU-4 (Digitex Laboratory). The sampling frequency was 200 Hz for motion data and 1,000 Hz for EMG signals.

We recorded EMG signals corresponding to eight muscles : deltoid (DL), long head of biceps brachii (LB), short head of biceps brachii (SB), long head of triceps brachii (LT), brachioradialis (BR), flexor carpi radialis (FC) and extensor carpi radialis longus (EC).

The measured marker positions were low-pass filtered by second order Butterworth filter with a cutoff frequency of 10 Hz. Angular position, angular velocity and angular acceleration of each joint were calculated from the marker positions. The EMG signals were also low-pass filtered by the same Butterworth filter and then rectified.

It is generally said that one throwing motion consists of three phases: the aiming phase, the take-back phase, and the throwing phase. We particularly focused on the time when the aiming phase and the take-back phase was switched, and defined it as the end of the take-back phase by finding the time when the vertical velocity of the hand tip in the world coordinates became zero. All recorded data were aligned at this switching time from the take-back phase to the throwing phase.

C. Optimization criteria

Recorded data were analyzed in terms of the following optimization criteria.

1) Sum of squared jerk: Minimum jerk is an optimization criterion proposed by Flash and Hogan [4] to explain human motor control. It is known that it precisely explains human reaching movements as long as there is no interaction with external objects. In this study, the arm of each subject did not interact with an external object, except a dart. Because the weight of a dart is much lighter than an arm, throwing trajectories may be well explained by this criterion. The objective function of the minimum-jerk optimization is defined in the task (world) coordinates, and is integration of the squared jerk of a hand for each coordinate during an arm movement.

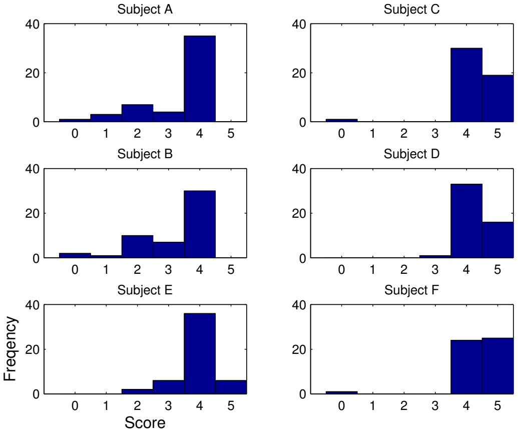


Fig. 2. Score distribution of all subjects

In this study, we used

$$C=\frac{1}{2}\sum_{k=t_s}^{t_f}\left(z[k+3]-3z[k+2]+3z[k+1]-z[k]\right)^2, \tag{1}$$

for calculating the objective function of the minimum-jerk criterion, where z is the discrete-time variable for the hand position in the vertical direction. t_s is the starting time of a throwing motion and t_f is the ending time.

2) Sum of squared joint-torque change: To overcome the problem of the minimum-jerk criteria which is purely kinematic, minimum torque-change criterion was proposed by Uno, et al. [5] to cover the minimum jerk trajectory model's demerits. The objective function of the minimum torque-change optimization is defined in the joint coordinates, and is integration of squared joint-torque change for each joint during an arm movement. The objective function was defined as

$$C=\frac{1}{2}\sum_{k=t_s}^{t_f}\left(\tau[k+1]-\tau[k]\right)^2, \tag{2}$$

where τ_i is joint torque of the ith joint, t_s is the starting time of a throwing motion and t_f is the ending time.

We estimate joint torques by inverse-dynamics calculation with the Newton Euler method. The upper-limb was modeled by three segment mechanical links with five degrees of freedom (DOFs). The shoulder joint was modeled as a 3 DOFs ball-and-socket, and the elbow and the hand joint were modeled as 1 DOF hinges. Required parameters of mass, center of mass (COM) and inertia were set based on body length and body mass according to [3].

III. RESULTS

A. Scores

Fig. 2 shows each subject's score. Subjects C, D and F (right panels) hit the bull's eye better (over 30% of throws) than other subjects A, B and E (left panels). Hence, we

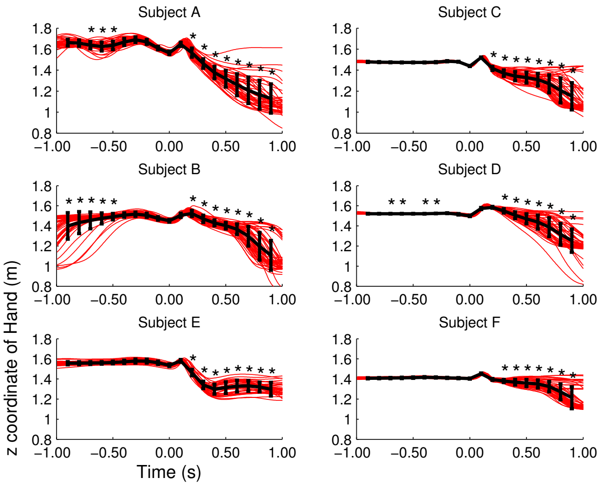


Fig. 3. Trajectories of the hand tip of all subjects

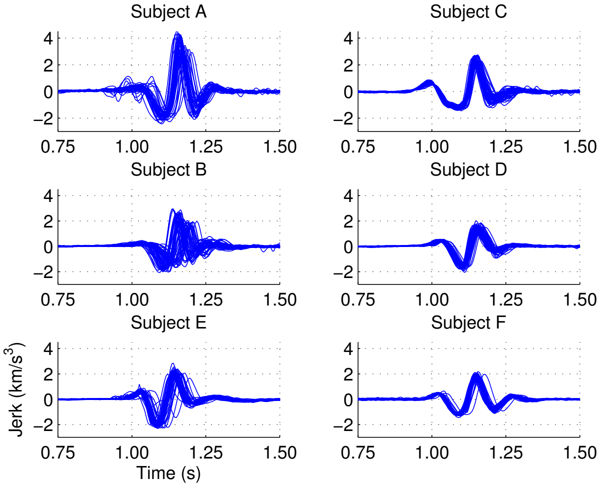


Fig. 4. Jerk trajectories of the hand tip of all subjects

decided to classify the subjects into two groups: C, D and F were experts and subjects A, B and E were non-experts.

B. Hand Trajectory

In Fig. 3, each panel shows whole trajectories of the z-coordinate of each subject's hand during one throw consisting of aiming, take-back, and throwing phases. Hand trajectories are shown by the red lines. Each black error bar shows the variance at a time over trajectories. The left three panels were of non-experts and the right three panels were of experts. '*' indicates the time points where their variance was shown to be significantly different from the variance at the switching time ($p < 0.05$). This figure clearly shows the significant difference between the experts and the non-experts such that the experts' variance of the hand position in the aiming and take-back phases was much smaller than that of the non-experts.

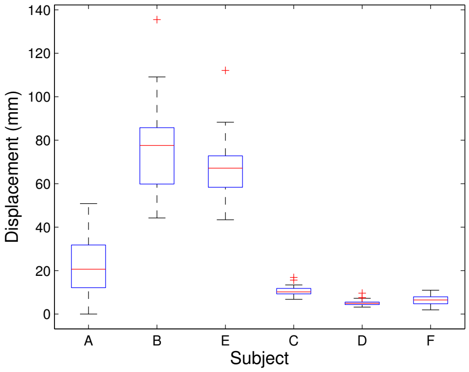


Fig. 5. Distributions of the shoulder displacement toward the darts board of all subjects

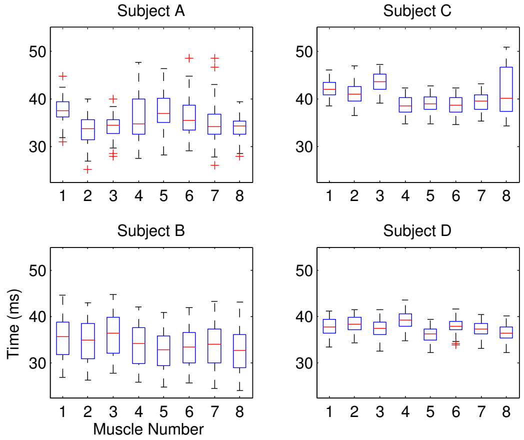


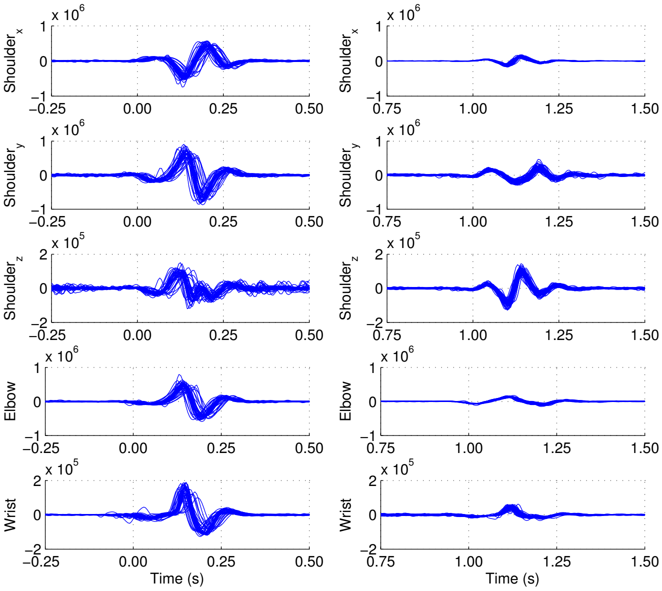
Fig. 6. Distributions of the activation-starting time of EMG signals of each muscle

C. Jerk Trajectory

Fig. 4 shows hand jerk trajectories of all subjects. The left three figures were of the non-experts, while the right ones were of the experts. The trajectory amplitude of subject A seems the largest, while both trajectory variances of subjects B and D seem large. The amplitude of vibration and wave pattern were different among subjects. Moreover, significant correlation was not found between the sum of squared jerks and scores of all subjects.

D. Shoulder Displacement

Fig. 5 shows the displacements in the horizontal plane of the shoulder during the throwing phase of each subject in the form a of box-plot. The horizontal axis corresponds to the subjects. This figure clearly shows the displacement of non-experts (A, B and E) was bigger than that of experts. The correlation coefficient between the mean score and the mean displacement over all subjects was -0.6625, suggesting that the smaller the displacement of the shoulder is, the higher the score is.



(a) (b)

Fig. 7. Estimated joint torque change trajectories of an expert (a) and a non-expert (b)

E. Muscle Activation Time

Fig. 6 shows an example of muscle-activation starting time of non-experts and experts. Along the horizontal axis, each number corresponds to DL, LB, SB, LT, BR, FC and EC. Roughly speaking, the muscle number increases as it moves away from the body trunk toward the periphery. Neither non-experts nor experts showed PDS, although. It seems that muscle-activation starting time of the experts was more accurate than that of non-experts.

F. Joint Torque Change

Estimated joint-torque change trajectories of subject F (expert, right panels) and subject A (non-expert, left panels) are shown in Fig. 7. Five panels in each column correspond to 3 DOFs shoulder-torque trajectories of all throws, 1 DOF elbow-torque trajectories and 1 DOF hand-torque trajectories, respectively. This figure clearly shows that the variance of the non-expert's torque-trajectory was higher than that of the expert. In contrast to the case of the sum of squared jerk, significant correlation was found between the scores of all subjects and their sum of squared torque-change values around the shoulder joint (rotation around x-axis and y-axis), the elbow joint, and the hand joint. The correlation values were -0.26, -0.17 and -0.19 ($p < 0.05$).

As shown in Fig. 1, subjects stood with their right shoulder forward. With this standing posture, rotation around the x-axis of the shoulder joint corresponds to elevating motion and is caused by shoulder adduction and abduction. Rotation around the y-axis of the shoulder joint also corresponds to elevating motion and is caused by horizontal shoulder flexion and extension. It is reasonable that these two axes of the shoulder joint were elaborately controlled for throwing darts because they mainly contributed to the throwing motion, while rotational arm motion around the z-axis should not. The obtained negative correlation between the sum of squared torque change and the scores of all data suggests that the experts optimally controlled the shoulder elevations, rotation around the elbow, and rotation around the hand joint, in terms of the dynamics, for throwing darts.

IV. CONCLUSION AND FUTURE WORK

In this paper, we compared skills in throwing darts between experts and non-experts based on their scores, motions, and EMG signals. We found that the variance of upper-limb trajectory of the experts was significantly smaller than that of the non-experts, and that the displacement and its variance of the experts' shoulder position was also significantly smaller than that of the non-experts. The most interesting finding of this study was acquired by analyzing the upper-limb motions of all subjects in terms of trajectory optimization criteria. That is, their sum of squared joint-torque changes was negatively correlated with their scores ($p < 0.05$), whereas their sum of squared jerks was not, suggesting that the experts optimally controlled the shoulder elevations, rotation around the elbow and the hand joint in terms of dynamics. In contrast to the previous studies, PDS was not found in their EMG signals, although the starting time of the experts' EMG signals was accurate over the trials. Our work in the near future will involve investigating other indices such as joint stiffness and energy consumption.

V. ACKNOWLEDGMENTS

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