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Throwing Darts Utilizes the Interaction Torque of the Elbow Joint

Tomoya Tamei, Chihiro Obayashi and Tomohiro Shibata

Abstract— **Acquiring the skillful movements of experts is a difficult task in many fields. If we find quantitative indices of skillful movement, we can develop an adaptive training system using the indices. We focused on throwing darts in our previous study. It was found that optimization criteria of sum of squared joint torque changes over time was negatively correlated with subject's scores, suggesting that the experts optimally controlled the shoulder elevations and rotation around the elbow joint in terms of dynamics. In this study, we investigate the relationship between the skill level of subjects and their utilization joint torque components such as the muscular torque, interaction torque and gravity torque. It is shown found that the sum of squared joint torque components of the subjects correlates with their scores, suggesting that the subjects who can take higher scores utilize the interaction torque of the elbow joint without shoulder displacement.**

I. INTRODUCTION

Recently, throwing motions of experts and non-experts have been compared on the basis of biological information such as motion and electromyographic (EMG) signals. For example, it has been found that expert baseball players efficiently use interaction torque in throwing a ball to generate higher ball velocity [1]. Additionally, experienced pianists utilize more interaction torque and gravity torque than beginners in generating the same level of loudness to reduce muscle loading [2] [3]. In this paper, we investigate the dart-throwing motions of six subjects having varying proficiency. We chose dart throwing as the activity for study because it is inherently different from ball throwing, which has been studied previously. Throwing darts is a simple action because it is usually performed by fixing the body trunk and is primarily driven by an upper limb. A dart is much lighter than a ball, and the acceleration required at the hand tip to throw a dart is much less than that for a ball. The possibility of muscle fatigue is much lower in throwing darts. Hence, the effect of fatigue on muscle activity should be much less in throwing darts. Smeets et al. performed sensitivity analysis of movement parameters such as the radius of curvature and time of release for the final dart position, and found that timing is not a critical factor of precision in dart throwing [4]. On the other hand, Obayashi et al. investigated relationships between optimization criteria of the upper-limb trajectory, such as the sum of squared jerk and sum of change in the squared joint torque over the trajectory, and task achievement (scores) [5]. They found correlation between the sum of the change in squared joint torque over the trajectory and task achievement, and suggested that the experts optimally controlled the shoulder elevations and rotation around the elbow in terms of dynamics. However, they did not study dynamic interactions among multiple joints.

To control joint movement optimally, it may need to utilize torque components. Although net torque (NET) is determined from only muscle torque (MUS) and gravity torque (GRA) in a single-joint movement, interaction torque (INT) is generated by other-joint movement in multi-joint movement. INT and GRA are passive torques influenced by the environment and adjacent joints, and thus, central nervous system (CNS) cannot control them directly. To avoid an injury and also reduce a signal-dependent noise [6] in a motor command, we hypothesized that experts utilize more passive torques for using less MUS in throwing darts same as throwing a ball [7] and a piano keystroke [2] [3]. In this paper, we investigate the different utilization of each torque component in each subject depending on the subject's skill level.

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

II. METHOD

A. Subjects

Three experienced and three novice subjects (adult males, age 25 ± 1 years) with different skill levels in throwing darts participated in the experiment.

B. Experimental setup and data preprocessing

Soft-tip darts were used in the experiment. The task was to shoot a bull's eye on a dartboard. The setting of the dartboard and the standing location of the subjects followed the official rules of the World Darts Federation as shown in Fig. 1. Scores for a dart landing in the bullseye, inner single ring, triple ring, outer single ring and double ring are 5, 4, 3, 2 and 1 point respectively (Fig. 2). A throw that misses the dartboard scores zero points.

Subjects were instructed to shoot for the bullseye with their preferred rhythm. Before the actual task, the subjects were asked to throw darts 30 times. The actual task consisted of 12 trials. In one trial, the subjects threw four darts one by one.

We used a PC DARTS system (Epoch Co., Ltd.) consisting of a board with a universal serial bus connection to a

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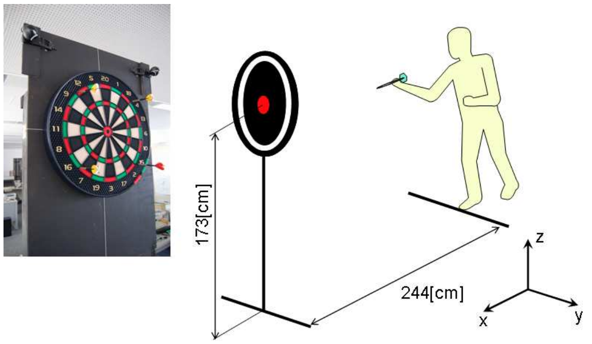


Fig. 1. Setting of the dart board and the standing location of the subjects

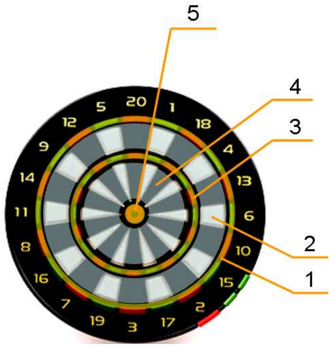


Fig. 2. Scoring system

personal computer, and darts with a soft tip. The scores were automatically calculated by the PC DARTS system. We used a MAC3D system (Motion Analysis Corp.) to measure the upper-limb motion with a sampling frequency of 200 Hz. Markers for optical motion measurement were attached to each subject's upper limb (shoulder, elbow, and hand).

The measured marker positions were low-pass filtered by a 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.

It is generally considered that the dart-throwing motion consists of three phases: the aiming phase, take-back phase, and throwing phase (see Fig. 3). We particularly focused on the timing of the transition from the take-back phase to the throwing phase, and defined the end of the take-back phase as the time when the vertical coordinate of the hand tip in world coordinates was a minimum (see the dashed line in Fig. 3). All recorded data were aligned with this transition time from the take-back phase to the throwing phase.

C. Throwing-phase extraction

In this paper, we focus on only the throwing phase for analysis of the relationship between the motion and skill level, because the hand tip (the dart) velocity becomes zero at the shifting moment from the take-back phase to throwing phase, and only the throwing phase gives a dart kinetic energy. However, our current measurement system could not determine the timing of the dart release, and thus, we determined the timing of release from motion data. We defined the throwing phase as the period in which the height of the hand's marker goes from a minimum value to a maximum value (see Fig. 3).

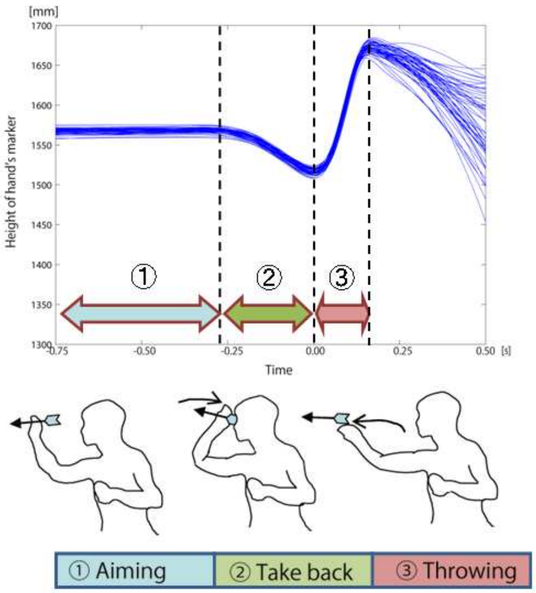


Fig. 3. Motion phases for throwing darts

D. Joint torque calculation

We calculated NET, GRA, INT and MUS in an inverse-dynamics calculation employing the Newton–Euler method [2]. The upper limb was modeled as three mechanical links with five degrees of freedom (DOFs). The shoulder joint was modeled as a three-DOF ball-and-socket, and the elbow and hand joints were modeled as one-DOF hinges. Required dynamic parameters of mass, center of mass and inertia were based on the body length and body mass according to [8]. Kinematic data such as joint angles, joint angular velocities and joint angular accelerations were calculated from motion-capture data.

We defined right-handed coordinate systems on the subject's body as in Fig. 4. Subscripts of O, S, E and W for x, y and z coordinates indicate global, shoulder, elbow and wrist coordinates respectively. Rotation arrows on the global coordinate axes indicate the positive rotation direction for each axis. The shoulder coordinates were determined such that a line connecting the right shoulder's marker to the left shoulder's marker is the y direction. Elbow and wrist joints should rotate around their respective y-axes.

E. Joint torque component criteria

Calculated joint torque components were analyzed in terms of the following criteria. The objective function is the integral of the squared joint torque for each torque component and joint during an throwing movement:

$$C_{ij} = \frac{1}{2}\sum_{t=T_s}^{T_f} \tau_{ij}(t)^2, \qquad (1)$$

$$(i = \mathrm{MUS},\ \mathrm{NET},\ \mathrm{INT}\ \textit{and}\ \mathrm{GRA})$$

$$(j = \mathrm{Shoul_x},\ \mathrm{Shoul_y},\ \mathrm{Shoul_z},\ \mathrm{Elbow}\ \textit{and}\ \mathrm{Wrist})$$

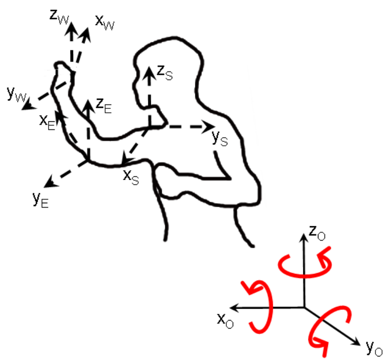


Fig. 4. Coordinate systems

where τ_{is} is the jth torque component of the ith joint, T_s is the start time of the throwing motion and T_f is the end time.

III. RESULTS

A. Scores

Fig. 5 shows each subject's score distribution. Subjects C, D and F hit the bullseye more often (over 30 % of throws) than the other subjects A, B and E.

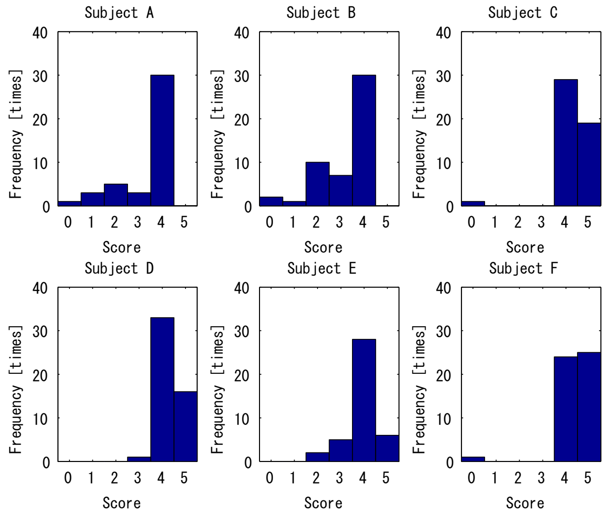
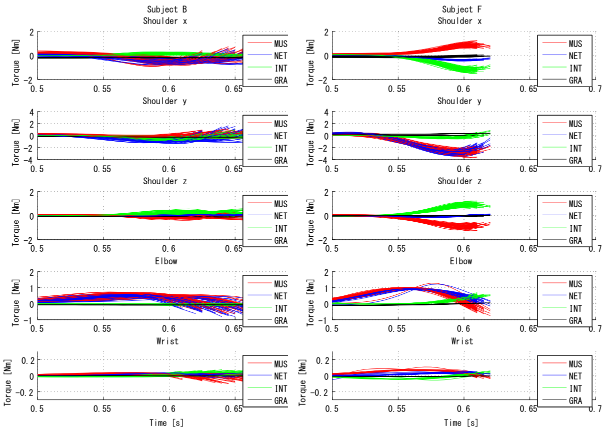


Fig. 5. Score distribution of all subjects

B. Joint torque components

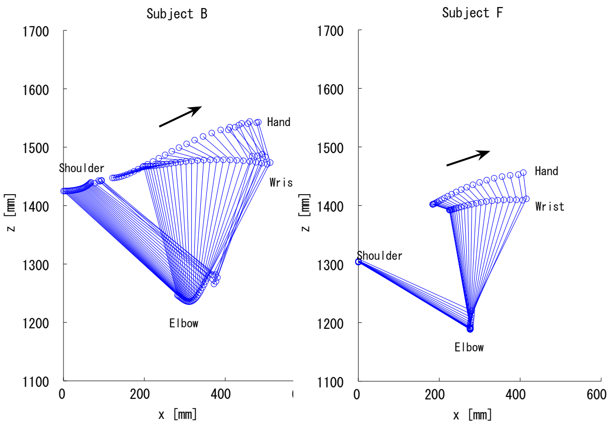
Trajectories of joint torque components in the throwing phase for subject B and F are shown in Fig. 6. Fig. 7 presents stick pictures of the upper limb motion averaged over all trials during throwing phase for subject B and F. Each circle indicates the markers for motion capturing. Five panels in each column correspond to the three-DOF shoulder joint torque trajectories and 1-DOF elbow and wrist joint torque trajectories for all throws. The figure clearly shows that the variance in joint torque trajectories of the higher score subjects (C, D and F) was less than that for other subjects (A, B and E).



(a) Subject B

(b) Subject F

Fig. 6. Joint torque components during the throwing phase



(a) Subject B

(b) Subject F

Fig. 7. Averaged motion during the throwing phase

C. Correlation with joint torques

Fig. 8 shows the coefficients of correlation between joint torque component criteria averaged over all trials and the average score of each subject.

IV. DISCUSSIONS

In the case of a piano keystroke, Furuya et al. [3] found that the elbow extension muscle (triceps brachii) was not activated when elbow extension torque was generated by pianists. Moreover, pianists reduced anti-gravity (biceps brachii) muscle activity with an increase in the loudness level. These results suggest that elbow extension torque was generated by gravity without the contribution of the elbow extension muscle (triceps brachii). Different from the case of piano keystroke, novices the present study found the utilization of joint torque components in throwing darts. GRA of each joint except the wrist joint had high negative

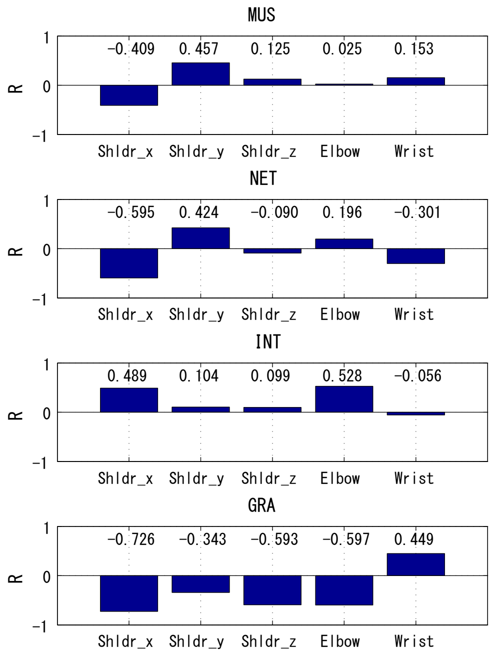


Fig. 8. Correlation between average joint torques and scores over all trials

correlation with the skill level in contrast with the case for the piano keystroke, while the wrist joint had positive correlation. Instead, INT of the elbow joint had high positive correlation with the skill level. The subjects who took higher scores tended to employ greater INT for elbow extension as was the tendency for a piano keystroke, because INT of the elbow is positive (working in the direction of extension) in the throwing phase. INT of the elbow would be generated by the torque around the y-axis of the shoulder joint, since the torque around the y-axis of the shoulder joint apply to raise the upper arm (see Fig. 6 and 7). It seems reasonable to restrict shoulder (trunk) movement during the throwing phase and to generate torque required to throw darts at the elbow joint, because only the accuracy of hit position is required in throwing darts, and much throwing speed is useless. Obayashi et al. also found that experts do not move their shoulder during the throwing phase [5].

Additionally, in the cases of subjects B, D and F, MUS of the elbow changes from the positive to the negative value before the end of the throwing phase (peak of the hand vertical trajectory) (see Fig. 6). This indicates that these subjects halted their elbow extension with their muscles to generate INT of the wrist, and the INT of the wrist was then cancelled by MUS. These torque patterns were also observed in throwing a ball that is required control accuracy; Hirashima et al. reported these patterns and concluded that wrist movement was restrained to control finger movement and the ball direction [7] by maintaining the muscle lengths of fingers. However, this torque pattern was not found for other subjects (A, C and E) and had no correlation with skill level. MUS of the elbow, and MUS and INT of the wrist were also uncorrelated with the skill level. These results show how a strategy for CNS is adopted specific to throwing darts.

This paper investigated the relations between the utilization of joint torque components and the skill level of subjects in throwing darts. It was found that the sum of joint torque components over time during the throwing phase was correlated with skill level by performing group analysis. However, the analysis carried out in this paper has some limitations. We found that the subjects in the same skill level could have different joint torque patterns, which may be due to a difference in throwing form and personally preferred throwing speed. Different body parameters should affect the joint torque pattern even if the kinematics data are the same. Thus we need further individual analysis by increasing the number of subjects. We also need to consider the temporal aspects of the joint torque.

As described before, Furuya et al. suggested that pianists drop their forearms by utilizing gravity effectively and they presented different muscle activation (EMG) patterns for generating joint torques for experienced pianists and novices. We also plan to measure EMG signals and analyze muscle activation patterns specific to the skillful throwing of darts. Another future work is to investigate optimal movement trajectories and muscle activation patterns using the subject's musculoskeletal model with the objective function of throwing darts accurately, and compare with actual throwing data. We shall also consider other indices such as joint stiffness and energy consumption. The application of the findings in this paper to adaptive training system is also planned in the near future.

V. ACKNOWLEDGMENTS

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