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Analysis of Human Motor Skill in Dart Throwing Motion at Different Distance

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Abstract: For medical or sports applications, human motor control is frequently analyzed. In this study, we focus on dart throwing motion and investigate the human motor skill to achieve precision control and force generation. The joint coordination is related to stability and accuracy of movements for precision control. On the other hand, the joint correlation is related to transfer of forces and movements for force generation. Uncontrolled manifold (UCM) analysis was applied to evaluate the joint coordination and elucidate the joint which the throwers decrease the variability. Based on the result of UCM analysis, it was found that throwers had less variability on the finger position rather than wrist, elbow, and shoulder positions. Ten young people who did not play dart on regular basis participated in our experiment, and performed dart throws at five different throwing distances. In order to evaluate the joint correlation, normalized correlation coefficient between arm and lower body was computed at different throwing distances. This analysis showed that the correlation between elbow and ankle, or between elbow and knee, were increased at long throwing distance. From our results, in dart throwing motion, we elucidated that the longer throw induced the new motor control strategy of precision control and force generation.

Key Words: Motion Analysis, Joint Coordination, Uncontrolled Manifold Analysis, Joint Correlation, Dart Throwing

1. Introduction

In this paper, we investigate the human motor skill to achieve both precision control and force generation tasks. In order to develop medical or sports applications, human motor control is frequently analyzed. Especially, in many previous research, throwing motion have been intensively analyzed because it is one of the extremity activities [1][2].

In medical areas, recent interest in physical training to improve physical function has focused on full body activities, namely the integration of arm and lower body movements [3]. Mainly arm movements are involved with precision control and lower body movements are involved with force generation [1]. Originally, physical training for arm movements and lower body movements were conducted separately. For instance, arm trainings have been conducted in a seated position [4]. Similarly, training for lower body in a standing position seldom includes training for functional arm movements in reaching, grasping or other manipulation task [5]. However, in recent research, training for the lower body is suggested to be important for the full effective recovery of arm as well as lower body [6]. In addition, Carr et al. suggested that separate training of arm and lower body is inadequate for recovery of physical function [7]. Waller et al. and Meusel argued that throwing motion in a standing position can improve the ability of full body movements [3][8].

In addition, in sports areas, it has been argued that a good javelin thrower transfers forces from lower body to upper body during the delivery, using coordinated motion of the body segments [9]. Similarly, in the basketball shooting at longer shooting distances, Robins et al. reported a significant reduction in the variability of joint correlations between arm joints [10]. For shooting from a longer distance, a very similar movement pattern is required to achieve precise control. Hirashima et al. suggested that arm has a role of precision control and lower body has a role of force generation in baseball pitching [11]. Thus, in extremity sports activities, if people want to achieve high performance, it is important to acquire the ability of precision control and force generation.

The aim of this study is to understand the human motor skill under the condition to achieve both precision control and force generation. Therefore, we focus on dart-throwing motion because it is easy to play in small area, and necessary to utilize the ability of precision control and force generation.

In the next section, we introduce two analyses; one is uncontrolled manifold (UCM) analysis for the joint coordination and the other is normalized correlation coefficient (NCC) analysis for the joint correlation. Both of them are angle-based analyses. In our analyses, joint angles are calculated from measured coordinates of each body positions. Angle-based analyses which are applied in this study require time-series angle data.

In this study, we investigate the change of human motor skill, especially precision control and force generation, in dart-throwing motion at different throwing distances.

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2. Analysis Methods

Human motor skill can be divided into two functions of precision control and force generation [11]. Precision control requires the control of their joint freedom (joint coordination). Force generation requires the kinematic correlation of specific joints (joint correlation). Dart throwing motion has a little perturbation in a sagittal plane and were analyzed in only a frontal plane in the previous works [12][13]. Besides, in this study, we restrict and analyze the motion to 2-D space in a frontal plane (XY plane in Fig. 1). This restriction is necessary to promote not only arm but also leg motion. For these reasons, we analyze dart throwing motion in a frontal plane.

2.1 Joint Coordination Analysis for Precision Control

The joint coordination contributes stability and accurate movements. While people can achieve a specific task by controlling their redundant joint degrees of freedom (DOF), each joint is divided into two types; one is controlled, and the other is not controlled.

If each joint variability is analyzed, it can be understood how people achieve a specific and coordinative movement during controlling the joint DOF. In this study, an UCM analysis [14][15] is applied to dart throwing motion in order to investigate which body position are controlled and to evaluate the joint coordination. The UCM is a configuration space which is composed by the combination of variables (joint angles in this study) which contribute to a specific body motion.

In the UCM analysis, it is possible to investigate whether a certain joint is controlled or not controlled to achieve a specific multi-joint task. This investigation is important to analyze multi-joint movement because humans do not move their joints independently but they well coordinate the joints to achieve a motor task. If the analysis only focus on the independent perturbations of each joint coordinates, it could not determine how humans coordinate their several joints. However, in the UCM analysis, we can use a multiple joint data and clarify whether each joint is controlled or not. In this analysis, if a joint is within the UCM, this joint is considered to be controlled to achieve a specific multi-joint task. On the other hand, if a joint is not within the UCM, this joint is regarded to be not controlled.

There are innumerable number of the combinations of joint angles to achieve a specific shoulder position. Figure 1 shows examples of different combinations of joint angles of the link model representing human body which achieves the same shoulder position. Since three joint angles, right ankle angle

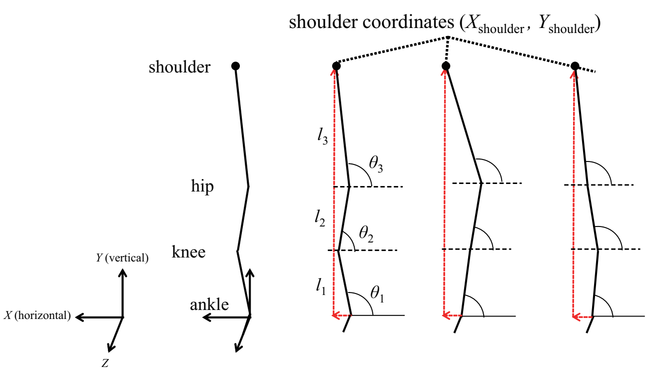


Fig. 1 Example of link model for same shoulder position

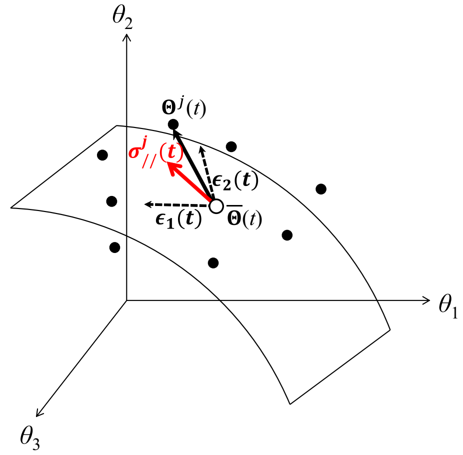


Fig. 2 Example of UCM analysis

(θ_1), right knee angle (θ_2) and right hip angle (θ_3) affect the shoulder position, the UCM consists of three dimensional space of each joint angle as shown in Fig. 2.

In this study, joint angle data is time-varying data and measured in several trials of each thrower. $\mathbf{\Theta}^j(t) = (\theta_1^j(t), \theta_2^j(t), \theta_3^j(t))$ indicates the combination of three joint angles in the j-th trial ($j = 1, 2, \cdots, N$) at certain time t, and mean joint angle within all trials indicates $\overline{\mathbf{\Theta}}(t) = (\overline{\theta}_1(t), \overline{\theta}_2(t), \overline{\theta}_3(t))$.

For example, Fig. 2 shows a UCM at certain time t_1 in dart throwing motion. In this case, the curved surface in Fig. 2 shows the combinations of joint angles, UCM, to achieve the same horizontal shoulder position $X_{\text{shoulder}}(t_1)$. This UCM is calculated based on the average shoulder position at mean joint angle within all trials, $\overline{\mathbf{\Theta}}(t_1)$ which was shown as white point in Fig. 2, at certain time t_1. Each black point in Fig. 2 shows the combination of three joint angles, $\mathbf{\Theta}^j(t_1)$, at certain time t_1 in each trial j respectively. If $\mathbf{\Theta}^j(t_1)$ are located in this surface, it means that the combination is coordinated in order to achieve the same shoulder position. On the other hand, if $\mathbf{\Theta}^j(t_1)$ are not located in this surface, that is an orthogonal direction of the UCM. It means that combination of joint angles is not coordinated and therefore it changes the shoulder position. Shoulder position is calculated based on a geometric link model as in eq. (1). In Fig. 1 and eq. (1), l_1, l_2, and l_3 indicate length of shank, thigh, and trunk, respectively.

$$\begin{bmatrix} X_{\text{shoulder}}(\mathbf{\Theta}(t)) \\ Y_{\text{shoulder}}(\mathbf{\Theta}(t)) \end{bmatrix} = \begin{bmatrix} l_1 \cos\theta_1(t) + l_2 \cos\theta_2(t) + l_3 \cos\theta_3(t) \\ l_1 \sin\theta_1(t) + l_2 \sin\theta_2(t) + l_3 \sin\theta_3(t) \end{bmatrix}. \quad (1)$$

In order to calculate distance between the UCM and a certain combination of joint angles, linear approximation around UCM is solved. The linearization is obtained based on the Jacobian of the geometric model at the reference configuration. This Jacobian is calculated as eq. (2).

$$\begin{bmatrix} \mathbf{J}_X^{\text{shoulder}}(\overline{\mathbf{\Theta}}(t)) \\ \mathbf{J}_Y^{\text{shoulder}}(\overline{\mathbf{\Theta}}(t)) \end{bmatrix} = \begin{bmatrix} -l_1 \sin\overline{\theta}_1(t) & -l_2 \sin\overline{\theta}_2(t) & -l_3 \sin\overline{\theta}_3(t) \\ l_1 \cos\overline{\theta}_1(t) & l_2 \cos\overline{\theta}_2(t) & l_3 \cos\overline{\theta}_3(t) \end{bmatrix}. \quad (2)$$

When Jacobian of either horizontal or vertical body positions is obtained as $\mathbf{J}_X^{\text{shoulder}}(\overline{\mathbf{\Theta}}(t))$ or $\mathbf{J}_Y^{\text{shoulder}}(\overline{\mathbf{\Theta}}(t))$, their null space $\mathbf{E}(t)$ is calculated from eq. (3). In the below sentences, we focus on the calculation of joint coordination for horizontal shoulder position. This is a space that does not change the horizontal shoulder position X_{shoulder}.

$$\mathbf{J}_X^{\text{shoulder}}(\overline{\mathbf{\Theta}}(t)) \cdot \mathbf{E}(t) = 0. \quad (3)$$

Columns of the matrix $\mathbf{E}(t)$ consisted of basis vector $\epsilon_{k\ (k=1,\ 2,\ \cdots,\ n-1)}(t)$ (n is a dimension of the vector $\mathbf{\Theta}$). Afterwards, as in eq. (4), $\sigma^j_{//}$ is obrained from the summation of the orthogonally projected vectors from $(\mathbf{\Theta}^j(t) - \overline{\mathbf{\Theta}}(t))$ to each basis vector $\epsilon_k(t)$ (Fig. 2).

$$\sigma^j_{//}(t) = \sum_{k=1}^{n-1}((\mathbf{\Theta}^j(t) - \overline{\mathbf{\Theta}}(t)) \cdot \epsilon_k(t))\epsilon_k(t). \quad (4)$$

The degree of joint coordination focused on a horizontal position of certain joint, S_X, is calculated by eq. (5). In eq. (5), a cosine among a joint angle vector, $(\mathbf{\Theta}^j(t) - \overline{\mathbf{\Theta}}(t))$, and a basic parallel vector, $\sigma^j_{//}(t)$, are used.

$$S_X = \frac{1}{N}\sum_{j=1}^{N}\frac{1}{T_{total}}\sum_{t=1}^{T_{total}}\frac{(\mathbf{\Theta}^j(t) - \overline{\mathbf{\Theta}}(t)) \cdot \sigma^j_{//}(t)}{|(\mathbf{\Theta}^j(t) - \overline{\mathbf{\Theta}}(t))\|\sigma^j_{//}(t)|}. \quad (5)$$

If the value of computed S_X is high, it is suggested that joints are well coordinated. In addition, we investigate the joint coordination in order to achieve the same vertical location of shoulder. In order to calculate joint coordination S_Y to achieve the same vertical location of shoulder, the same method was used as calculation of S_X.

This degree of joint coordination is calculated for the normalized time series (1-100%) of dart throwing motion. This study focuses on four points of body position; a finger, a wrist, an elbow, and a shoulder.

2.2 Joint Correlation Analysis for Force Generation

It is suggested that the correlation between two joints is required during full body movements, running [16], triple jumping [17], javelin throwing [18], and basketball shooting [18]. In the previous studies, in order to quantify the joint correlation, correlation coefficient between joints is calculated in human movements [19][20]. As kinematic correlation analysis, this quantitative method are effective evaluation. Thus, in this study, in order to understand how arm and lower body movements are correlated to achieve throwing motion at long distance, normalized correlation coefficient (NCC), $R(x, y)$, between arm data and lower body data at each trial were calculated as in eq. (6). As arm data ($x(t)$), right shoulder, right elbow and right wrist joint angles are used. As lower body data ($y(t)$), right-and-left hip, right-and-left knee, and right-and-left ankle joint angles are used. Both data are time-varying during throwing dart motion as shown in Fig. 3.

Figure 3 shows a schematic concept in order to explain our used data in analysis. In the meanwhile, Fig. 4 shows typical joint angle data used in our analysis. Figure 4 (a) shows the example of highly correlated combination of arm and lower body angle, and Fig. 4 (b) illustrates the example of the lower correlated combination of arm and lower body angle among all results of NCC analysis. In eq. (6), $\overline{x}$ and $\overline{y}$ indicate arithmetic average of $x(t)$ and $y(t)$ among total throwing motion from start timing to finish timing respectively.

If the absolute value of computed NCC between certain arm data and certain lower body data is high at a particular throwing distance, it is suggested that the degree of the correlation between them is high at this throwing distance.

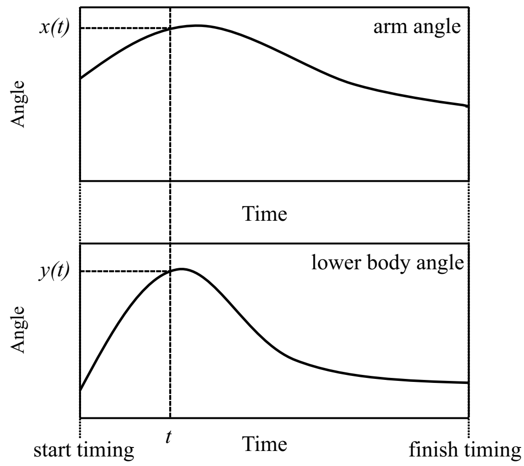
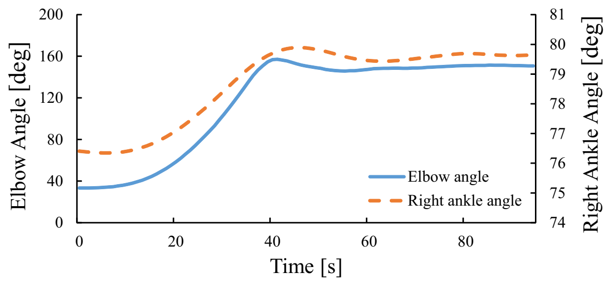
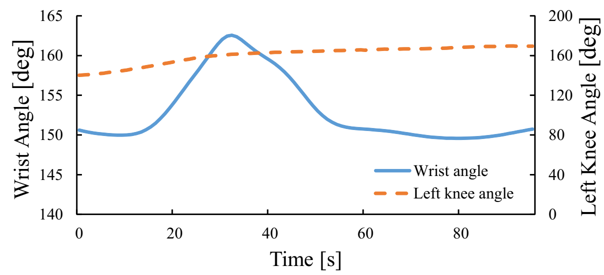


Fig. 3 Example of coordination evaluation with NCC



(a) Highly Correlated Pairs



(b) Lower Correlated Pairs

Fig. 4 Typical joint angle data used in our joint correlation analysis

$$R(x, y) = \frac{\sum_{t=1}^{T_{total}}(x(t) - \overline{x})(y(t) - \overline{y})}{\sqrt{\sum_{t=1}^{T_{total}}(x(t) - \overline{x})^2}\sqrt{\sum_{t=1}^{T_{total}}(y(t) - \overline{y})^2}}. \quad (6)$$

2.3 Definition of Motion

The duration of the motion is different in each throwing motion or among people. In order to compare different trials of dart throwing motion, the throwing data is normalized to 0-100%.

- The start time (0%)
  The first time at which the elbow joint angular velocity rises above zero.

- The finish time (100%)
  The first time at which the elbow joint angular velocity reduces to zero or less after the start time.

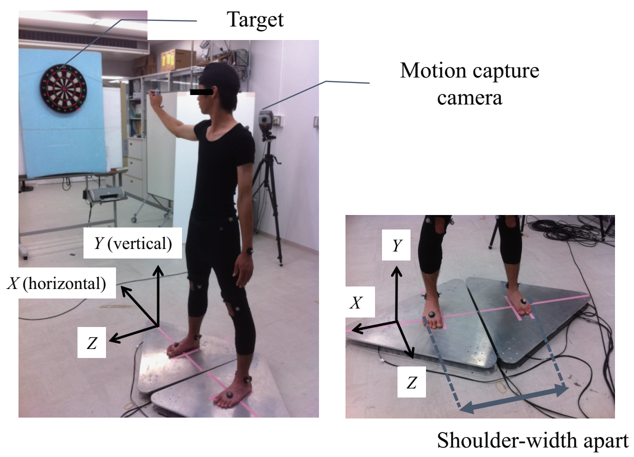


Fig. 5 Posture of participants

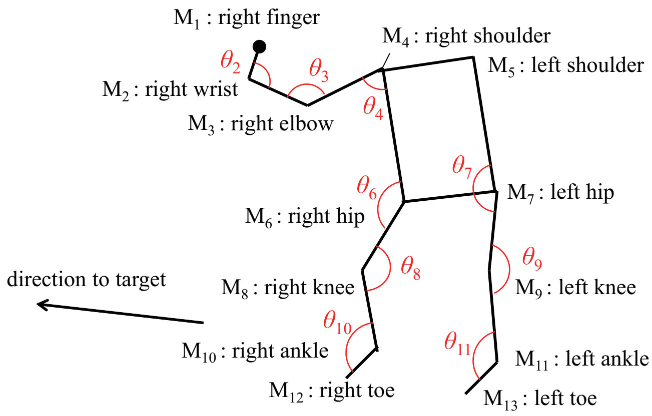


Fig. 6 Definition of position-markers and joint angles

2.4 Statistical Analysis

A one-way repeated analysis of variance (ANOVA) is performed to assess the degrees of joint coordination among different joints with post hoc two-sided Tukey's tests when appropriate. Likewise, ANOVA is performed to assess the degrees of joint correlation between arm data and lower body data at different throwing distances with post hoc two-sided Tukey's tests when appropriate. In order to evaluate statistical significance, significance level is set to $p < 0.05$ for the analyses.

3. Experimental Setup

In the previous section, we introduced two angle-based analyses. In order to analyze joint angles during dart throwing motion, we measured coordinates of joints with the optical motion capture system and calculated joint angles. In this study, as shown in Fig. 5, participants have sideways stance, with both legs turned in a vertical direction to the target (Z-axis) and shoulder-width apart. We instructed the participants to throw darts in a frontal plane (XY plane in Fig. 5).

According to the rules of the World Darts Federation, the throwing distance to the dart board is set to 2.4 m in normal darts game [21]. In this study, participants throw at distances of 1.2, 2.4, 3.6, 4.8, and 6.0 m. The throwing distances 3.6, 4.8, and 6.0 m are defined as long distances compared to the distance of normal darts game. On the other hand, the throwing distances 1.2 m are defined as short distances.

3.1 Participants

Totally, ten young people participated in our experiment. They were healthy right handed male (age: 24.0 ± 1.0 years old, height: 1.75 ± 0.08 m, weight: 68.0 ± 7.0 kg). They did not play dart on regular basis. They performed 10 dart throws at each throwing distance. Each participant threw darts to aim at the center of the dartboard. Consent was obtained from all ten participants before the experiment started, in compliance with the ethical committee of the Graduate School of Medicine and Faculty of Medicine, The University of Tokyo.

3.2 Data Measurement

In order to measure dart throwing motion, MAC3D System (Motion Analysis Corp.) was used. In this experiment, eight cameras were used for body trajectory measurement, and a calibration for accuracy confirmation was performed before the start of recording (less than 1.0 mm). Based on the rules of the World Darts Federation, the height of the center of the dart board was set to 1.73 m [21]. Thirteen points of body position, right middle finger (M_1), right wrist (M_2), right elbow (M_3), right shoulder (M_4), left shoulder (M_5), right hip (M_6), left hip (M_7), right knee (M_8), left knee (M_9), right ankle (M_{10}), left ankle (M_{11}), right toe (M_{12}), and left toe (M_{13}), were measured in this study. The sampling rate for this data was 200 Hz and nine joint angles were computed as shown in Fig. 6.

Joint angles were calculated using measured coordinates of body positions. Joint angles ($\theta(t)$) at the certain time t is arccosine of two vectors. For example, right shoulder joint angle ($\theta_4(t)$) was calculated from two vectors (vector from M_4 to M_3 and vector from M_4 to M_6).

4. Results

4.1 Result of Joint Coordination Analysis

In this study, four horizontal and vertical arm positions of a finger, wrist, elbow, and shoulder, were considered. Figure 7 shows averaged degrees of the joint coordination (S_X) for the horizontal positions of ten throws from ten participants at each throwing distance. Figure 8 shows averaged degrees of the joint coordination (S_Y) for the vertical positions of ten throws from ten participants at each throwing distance. In the figure, the bars indicate mean values with error bars which show a standard deviation, and asterisks above bars show two body joint positions in which there was a statistical significance ($p < 0.05$).

For horizontal and vertical positions of finger, the results show the joint coordination at all throwing distances were statistically higher than ones for wrist, elbow and shoulder ($p < 0.05$). Thus it was elucidated that throwers coordinate ankle, knee, hip, shoulder, elbow, and wrist joints in order to achieve a specific kinematics of finger position during dart throwing motion. In the case of wrist and elbow for either horizontal or vertical direction, the degrees of joint coordination at all throwing distances were statistically higher than one for shoulder ($p < 0.05$). For vertical position of wrist, the degree of joint coordination at each throwing distance were statistically higher than one for elbow ($p < 0.05$).

4.2 Results of Joint Correlation Analysis

Joint correlation analysis was applied to the data measured in each trial. Figure 9 shows the results of NCC analysis between elbow joint angle and other joint angles of legs ($R(\theta_3, \theta_8), R(\theta_3, \theta_9), R(\theta_3, \theta_{10})$, and $R(\theta_3, \theta_{11})$) at different

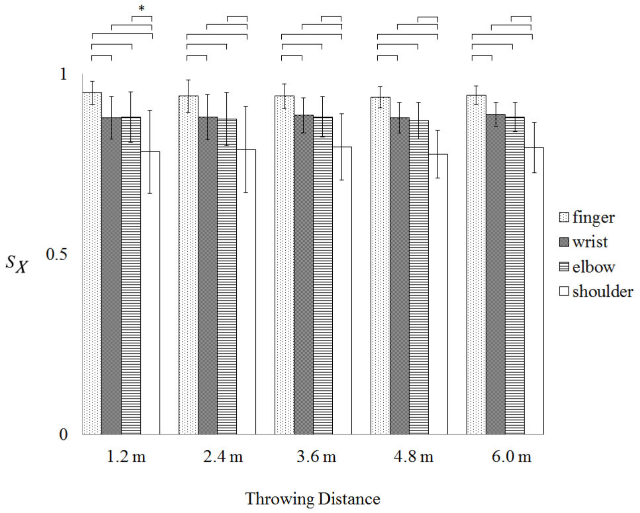


Fig. 7 Histograms of degrees of joint coordination for horizontal positions

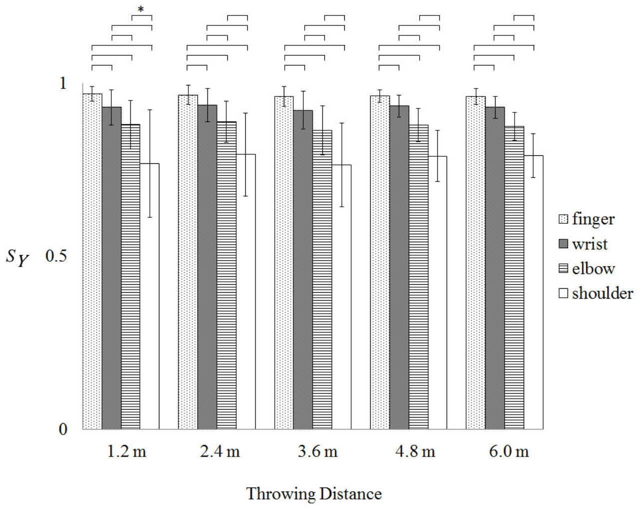
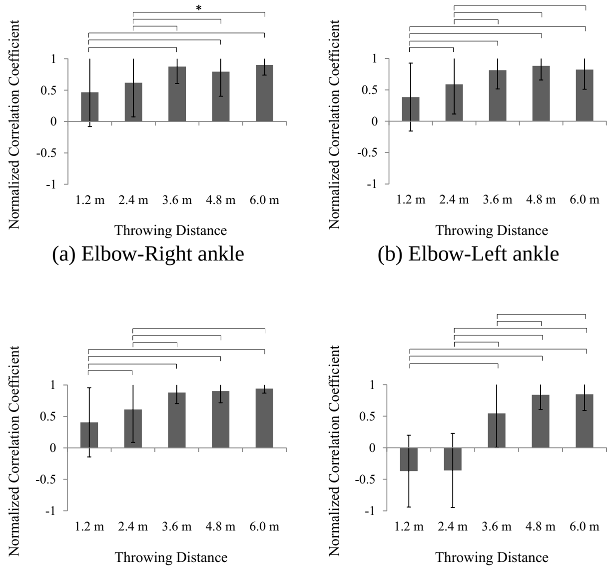


Fig. 8 Histograms of degrees of joint coordination for vertical positions



(a) Elbow-Right ankle (b) Elbow-Left ankle

(c) Elbow-Right knee (d) Elbow-Left knee

Fig. 9 NCC between elbow joint angle and each joint angle of both legs, knee and ankle

throwing distances. In these figures, NCC at each distance were averaged among all trials of ten participants and error bars show a standard deviation of each data. In the figures, asterisks above bars denote two throwing distances in which there was a statistical significance ($p < 0.05$).

Based on the results of the statistical analysis on $R(\theta_3, \theta_8)$, $R(\theta_3, \theta_9)$, and $R(\theta_3, \theta_{10})$, the degrees of the correlation were increased at throwing long distance (3.6, 4.8, and 6.0 m). On the other hand, based on the results of the statistical analysis on $R(\theta_2, \theta_{6,7,\cdots,11})$ and $R(\theta_4, \theta_{6,7,\cdots,11})$, the degree of correlation was no difference between throwing long distance and throwing short distance. However, these values were smaller than the cases of elbow. Thus, force for long distance throwing was generated by joint correlation between elbow and legs.

5. Discussion

In our analysis of joint coordination, four horizontal and vertical arm positions were considered. In particular, in order to decrease the variability of both horizontal and vertical finger positions, the joint coordination among wrist, elbow, shoulder, hip, knee, and ankle joint were utilized at all throwing distances. From the results of UCM analysis, it was elucidated that throwers controlled their joint positions in the order of finger, wrist, elbow, shoulder to aim the darts at the center of target. In addition, at all five distances, the results of each joint coordination showed the same trend. Regardless of throwing distances, the throwers mostly control their finger to realize precise control.

However, if throwers only controlled their joints position, they could not achieve the long distance throwing. From the results of joint correlation analysis, force was generated by joint correlation between elbow and legs at longer distance. The joint correlations between other arm joints and legs at longer distance were statistically smaller than the cases of elbow ($p < 0.05$).

In the previous research, it was suggested that an elbow joint has a function to achieve force generation [11]. Similarly our results suggested throwers generated force correlating elbow and legs movements at the condition which the ability was required.

Considering the effect of throwing distance, the joint correlation was increased in the longer darts throw. It indicated that humans moved their legs more dynamically to generate force from the legs to their darts throw. On the other hand, joint coordination remained higher especially in finger control even in the longer distance. It could be suggested that the longer distance induced the new motor control strategy of force generation besides precision control. Moreover, it implied that humans could utilize both strategies of precision control and force generation at the same time.

6. Conclusion

In this study, we have focused on a dart throwing motion as an integrated movements of precision control and force generation. We investigated how people achieved precision control task and force generation, especially in dart throwing motion. Joint coordination and joint correlation were analyzed.

The UCM analysis was applied to dart throwing motion in order to investigate the precision control ability by joint coordination. As a result of UCM analysis, it was found that throwers decreased variability of joint positions in the order of finger, wrist, elbow, shoulder at all throwing distances. Therefore, people achieve precision control task by stabilizing a body part position which is close to the finger in throwing motion.

Next, in order to investigate the force generation by joint correlation, NCC between arm joint angles and lower body joint angles was calculated. In dart throwing motion at longer distance, it was found to be necessary to increase correlations between elbow and ankle, and between elbow and knee were increased. Thus, people generate force correlating elbow and legs movements at long throwing distance.

These results indicated that the longer throw induced the new motor control strategy of precision control and force generation. In our future research, we will measure and analyze dart-throwing motion on different conditions, changing a weight of dart arrows, foot stance or arm path.

Acknowledgment

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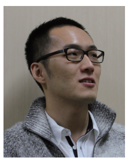

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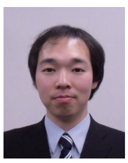

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