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A Study on Analysis of Biomechanical Factors in Skilled Dart Throwing

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Abstract

Recently, sports science has been intensively investigated due to the demand for professional games. It is worth understanding the underlying mechanisms of the brain and motor system of human, which attribute skills and strategies of experienced players to improve the performance of athletes and coaching practice. This thesis investigates biomechanical factors in dart throwing to gain insight into motion expertise in terms of kinematics and muscle activities.

Kinematics parameters and electromyography (EMG) of eight skilled dart throwers were simultaneously recorded by a motion capture system and EMG recording system while performed a task of 42 throws. A system of six high-speed cameras was used to capture movements of the trunk, shoulder, elbow, wrist, thumb, and dart. The kinematic data were synchronized with EMG signals of eight muscles along the throwing arm. Vertical error curves derived from the hand and dart trajectories were calculated for timing sensitivity analysis to distinguish the strategies of the experts. Moreover, in EMG analysis, muscle activities of *Biceps brachii* (antagonist) and *Tricepss brachii* (agonist) at the elbow joint were investigated to evaluate the characteristic in the neuromuscular system of skilled throwers. That is, the antagonist muscle activity of the experts was relatively low as compared to novices. Additionally, muscle synergies in dart throwing movement were analyzed to provide evidence to the muscle synergy hypothesis.

Results showed that there were two throwing strategies according to the length of time-window for the successful release, i.e., small timing sensitivity and small timing error. These strategies were characterized by a spatiotemporal relationship between the hand and dart trajectory during the acceleration phase, the released dart's velocity, and wrist angular acceleration. In terms of EMGs, co-activation, which is considered as a negative phenomenon

in throwing task, was relatively low in experienced throwers as compared to the beginners. Clarifying characteristics of experts' strategies would be informative for scientists in motor control. Furthermore, three muscle synergies were identified to explain sufficiently the observed EMG data of ten individual muscles, which could support the hypothesis.

This thesis is the first study that has elucidated strategies of high skilled dart throwers by a comprehensive analysis on kinematic parameters of human joints, hand and dart trajectories, and muscle activations.

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Chapter 1. Introduction

1.1 Background

Sports science has played a critical role in enhancing performance due to the demand for effectiveness and accuracy of human movements. In high competitive games in sports, which has received a great deal of attention nowadays, the expertise of movements attributes to skills indeed becomes a key for player development [1]. A wide range of sub-disciplines in sports science such as biomechanics, motor control, and performance statistics, has been intensively investigated to comprehend and improve movement quality quantitatively. It is appealing to examine fundamental mechanisms of the human motor system which influence the outcome, which could provide advantages for athletes as well as practical training methodology for novices to improve performance.

In goal-oriented sports like basketball or dart, which requires an extreme accuracy outcome, a skilled player has to coordinate the following movements elaborately: 1) Control the coordination between multiple joints and muscles on the upper limb. 2) Move the arm and dart simultaneously and appropriately. 3) Release a projectile at an appropriate speed and angle to achieve an accurate throw. Any tiny errors in the controlling among one of these factors could significantly affect the outcome [2], i.e., miss or no score. Therefore, the ability to elaborately combine several distinct factors of motor control into a singular throwing movement is worth being investigated from skilled players. Concurrently, muscle activity controlled by the neuromuscular system to control the upper arm should be economically coordinated to produce smooth movements. From the expertise required for skill acquisition, the author examined the biomechanics of experts in dart throwing to clarify how skilled dart throwers systemically control the upper limb movements to realize accuracy in the current thesis. In this thesis, dart throwing movement is chosen since it is a sophisticated skill, where untrained players cannot perform the task with consistently accurate performance. Moreover, the performance of the task is easily evaluated through the error measured on the dartboard.

In throwing tasks, the final position of a projectile is determined by the combination of initial values (location, speed, and direction) at the time of release. However, the kinematics parameters were mainly estimated by the movements of the hand and proximal joints. Hence, besides the ability to control the motor system, timing precision would be considered as one of the main factors that contributes to skills and strategies of experts [3].

Previous studies in throwing tasks have either investigated the kinematic parameters of the human joints or kinematics of a projectile at the time of release *separately* to detect the factors influence on the performances, to elucidate characteristics of the skills and strategies of experienced throwers [4-12]. Also, variables in a kinematic parameter could compensate for another parameter to achieve the same outcome [13-15]. In addition, for the analysis of timing sensitivity, researchers have proposed prediction models based on the hand movement to estimate the final position of the projectile in some throwing tasks [16-19]. However, a model based on the projectile trajectory, which could be more precise, has been still ambiguous. Furthermore, how the movements of human joints (e.g., the angular velocity of the wrist and elbow) and dart at the time of release reflex characteristics of strategies of skilled throwers have been ambiguous.

In electromyography (EMG) analysis, there is a hypothesis that decreased antagonist activation level is considered as an indicator of acquiring motor skills [20]. Thus, inter-group differences of the phenomenon in various skill levels in dart throwing are worth being elucidated to support the hypothesis. Moreover, muscle synergies in dart throwing were also investigated to gain insight into the hypothesis states that there was a small number of muscle groups to control recruited by the Central Nervous System to deal with the redundancy problem [13].

The current thesis is a comprehensive analysis that investigates the combination of kinematic parameters of human joints, hand, dart, and neuromuscular activities to elucidate the skills and strategies of dart experts.

1.2 The aim of the thesis

In this study, I investigated the skills and strategies of high-level experts in dart throwing in terms of kinematics and EMG signals. The current thesis aims to:

1) Propose a new prediction model based on the dart trajectory to clarify strategies of experts in dart throwing by timing sensitivity analysis, and demonstrate the advantages of this model as compared to previous ones.

2) Clarify whether experts who have less timing sensitivity pre-plan to spatially control the hand trajectory appropriately before the time of release, which implies that these throwers might have spatial control and less focus on timing precision. Meanwhile, hand paths of experts who have great timing sensitivity did not move in this manner.

3) Confirm that the strategies of experts by timing sensitivity are not only characterized the hand trajectory but kinematics parameters from human joints (i.e., elbow and wrist) and the dart (release speed and direction at the time of release).

4) Analyze the activation levels of the two muscles around the elbow joint, i.e., *Biceps brachii* (*BB*) and *Triceps brachii* (*TB*), to clarify how experienced control the muscle economically to produce a smoother drive in dart throwing. Moreover, muscle synergies were clarified to be clear expertise.

Elucidating these points could provide informative expertise applicable to other throwing sports.

1.3 Organization of the thesis

The thesis consists of five chapters.

Chapter 1 describes the background, the purpose, and the outline of this thesis.

Chapter 2 describes the literature review of the thesis. First, an overview of biomechanical related to sports science is presented. Afterward, the background of kinematics and EMG signals in throwing sports is presented, i.e., the previous methods, findings, challenges, and ambiguous points still have not been addressed, which is followed by hypotheses of this study. For easy to follow, I describe kinematics and EMG analysis separately in Chapter 3 and Chapter 4, respectively.

Chapter 3 elucidates the underlying characteristics of motor strategies and EMG signals of skilled players. This chapter mainly focuses on kinematic characteristics of skilled dart throwing. First, the methodology, i.e. the experiment design and procedure, data recording and processing, performance, criteria assessments to evaluate skills and strategies of the experts, is presented. In this part, I propose a new prediction model to estimate the final position of the dart on the dartboard, indicating the advantages and improvements of the proposed model compared to the previous studies. The model calculated the timing sensitivity and timing accuracy, which could classify the two strategies among the experts, i.e., increasing the time-window for the successful throw and reduce timing error. Each factor of the motor control, which reflexed the throwing strategies, is elaborately examined, e.g., release parameters of the dart and human joint.

Chapter 4 describes the patterns of muscle activities of inexperienced and intermediate dart players to clarify the differences between EMG patterns of these groups and experts. In the first part, the co-activation of the antagonist (*BB*) and agonist (*TB*) muscles of the elbow joint, which could be considered as a negative factor, was investigated. It is vital to investigate inter-group differences in the antagonist co-activation to test whether experienced players had a specific muscle activation or not. The second part elucidates muscle synergy analysis in dart throwing to support the muscle synergy hypothesis [13]. In both two parts, the methodology is depicted, which is followed by the results and discussions.

Chapter 5 describes the contributions to sports science, some limitations, and prospective studies throughout this thesis.

Chapter 2. Literature review

2.1 Biomechanical applications

Biomechanics, which is a sub-discipline of kinesiology, describes a movement of human or animals and how the force produces it [1], has been intensively investigated to understand mechanical aspects of living organisms. The research field has gained insights into several applications, e.g., as gait analysis, prosthetics, and rehabilitation in clinical [22-25]; movement simulation of animals in animation [26]; coaching and personal training in sports [27-28]; clarifying kinematic patterns of skill [29-33]. Figure 2-1 shows an example of the posture during a kick which was divided into four phases: *Preparation*, *Chamber*, *Extension*, and *Recoil Phases* [29].

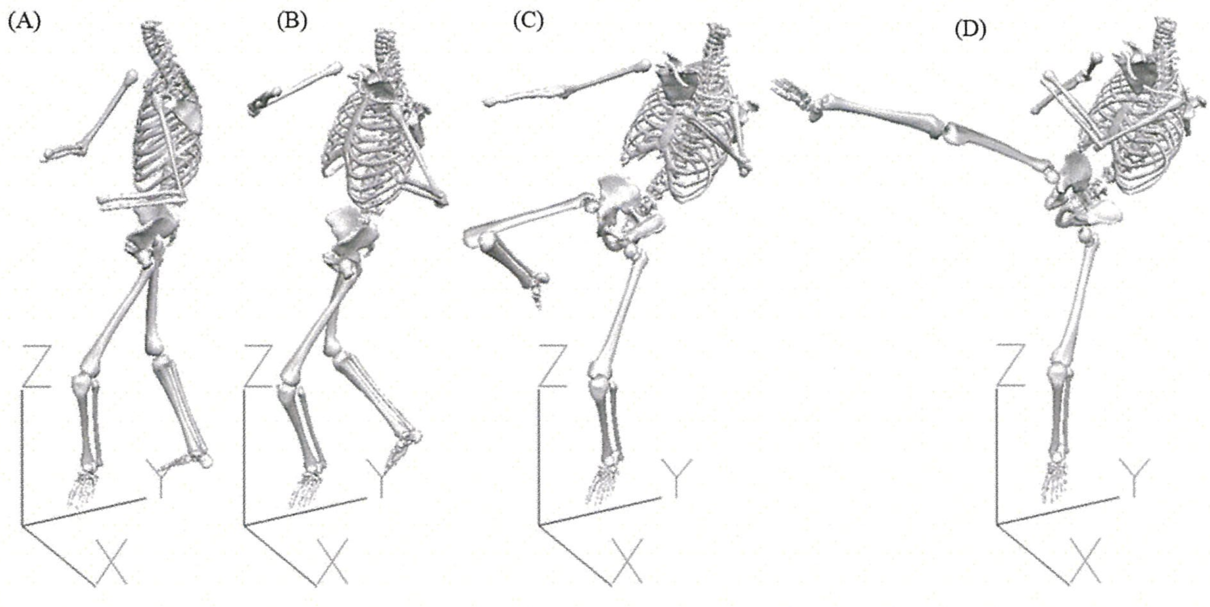

Figure 2-1. Example of the postures adopted by the participants at the Preparation (A), Chamber (B), Extension (C), and Recoil Phases (D) [29].

In sports sciences, biomechanical research applies physics and mechanical laws to comprehend mechanisms of the skeletomuscular system to enhance athletic performance and provide effective coaching. Also, biomechanics can be applied to the design of equipment and related facilities [30] such as shoes, tennis rackets, and swimming clothes. The equipment with advanced technology can enhance performance significantly. Moreover, biomechanics also can be used to study the force to prevent injury and increase the strength of muscles.

It is worth for specialists classifying skills and strategies of highly skilled experts while performing a task from the collected biomechanical information in engineering. From the expertise, novices would learn/imitate and then improve performance, or encounter opponents' strategies in professional games. For instance, in the baseball pitching study [31], movement patterns of athletes in terms of kinematics and kinetics were revealed among numerous participants (231 males).

Although movement performance of humans can be assessed from various factors such as anatomic, physiological capacities, psychology, cognitive abilities, and neuromuscular skills, biomechanics is the main sub-discipline to contribute to analyze human movement qualitatively [1]. In this study, *kinematics* and *electromyography* (*EMG*), the two applications of the biomechanical field, are investigated to gain insight into both outsides and inside patterns of the musculoskeletal system of experts during dart throwing.

2.1.1 Kinematics

Kinematics describes changes in positions of a subject without considering the force causing the motion [34], or a geometrical viewpoint. The information of location can be measured by linear or angular terms [1]. Kinematics is a brand of classical mechanics to assess movement sequences of human/animals quantitatively. Recently, modern wearable technology was developed to obtain the kinematic data of moving subjects in sports [39] such as inertial measurement units [35], flex sensors [36] and magnetic, angular rate and gravity (MARG)

[37-38]. Traditionally, motion capture systems with high-speed cameras are usually utilized to track biomarkers [40] attached on anatomical landmarks of the body. Corresponding multi markers represent segments of the human body, and information (location or coordination) of moving objects is measured within a calibrated space. Figure 2-2 shows markers attached on the body of a fence who was preparing to lunge [28].

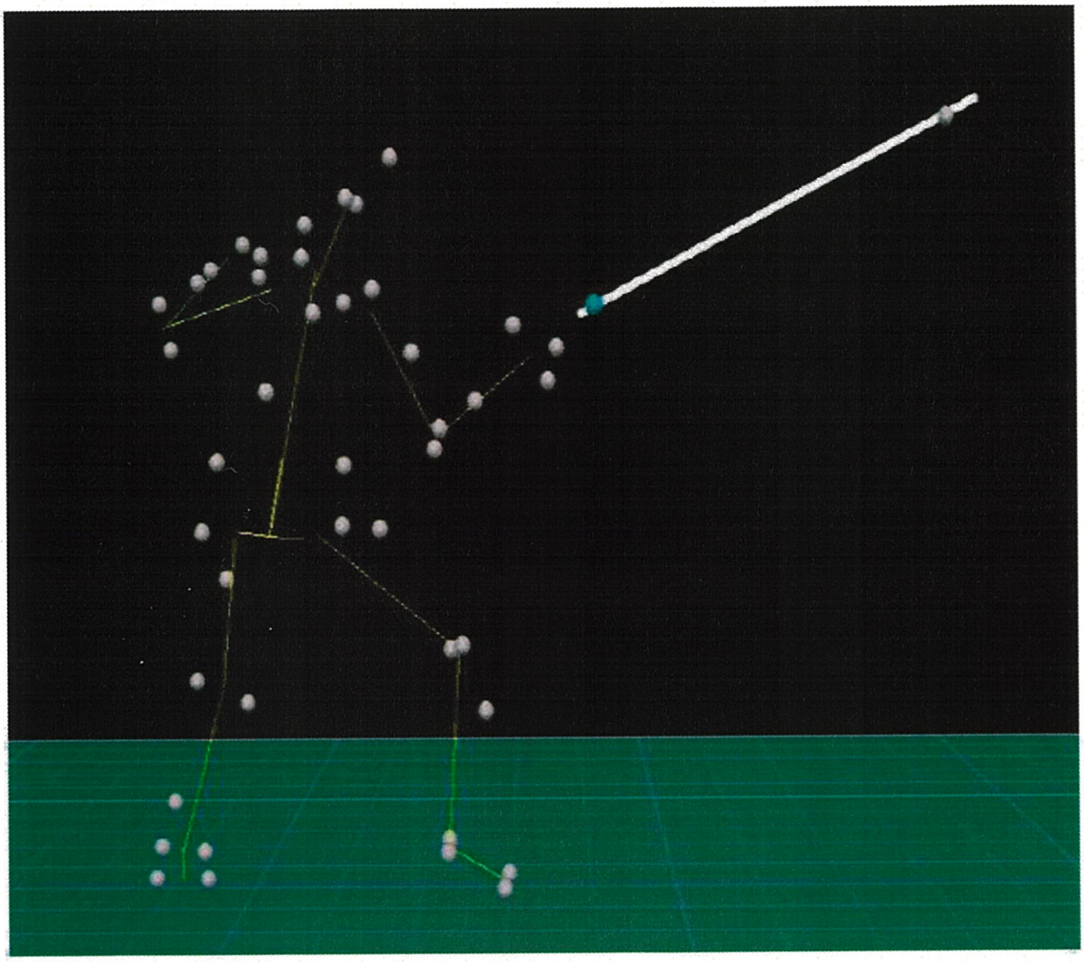

Figure 2-2. Body markers and stick figure of fencer in preparation for a lunge [28].

In sports science, skills and strategies extracted from experts' motion lead to consistent and superior performance. After extended and intensive practice, experts could realize and detect the critical factors of motion to obtain the high level. Therefore, it is important to elucidate the underlying movement patterns by qualitative analysis of kinematic parameters such as location, speed, acceleration, and jerk, in both linear and angular variables. The expertise can be useful for coaching practice and enhancing the performance by visual feedback.

2.1.2 Electromyography

Electromyography (EMG) is a technique measures bio-electrical signals during muscle contractions. A raw EMG signal is the summation of several motor unit action potentials (MUAPs) detected by an electrode pair [41]. The electrical activity enables to detect and diagnose potential clinical problems, improve the quality of locomotion as well as reduce the incidence of injury [42]. There are two kinds of techniques to record EMG: surface and intramuscular EMG. The former is more prefer to record electrical activity of superficial muscles and non-invasive, thus has been frequently used in sports. Surface EMG signals were used to serve a wide range of applications such as gait analysis [43-45], evaluating muscle fatigue [46-48], clinical [49-51], prosthetic arm [52-53], and sports [54-55]. In sports science field, more and more investigations utilizing EMG techniques have published, with over 2500 research publications each year, in 2013 (see Figure 2-3), proving the importance activities of muscles to produce a movement to improve performance.

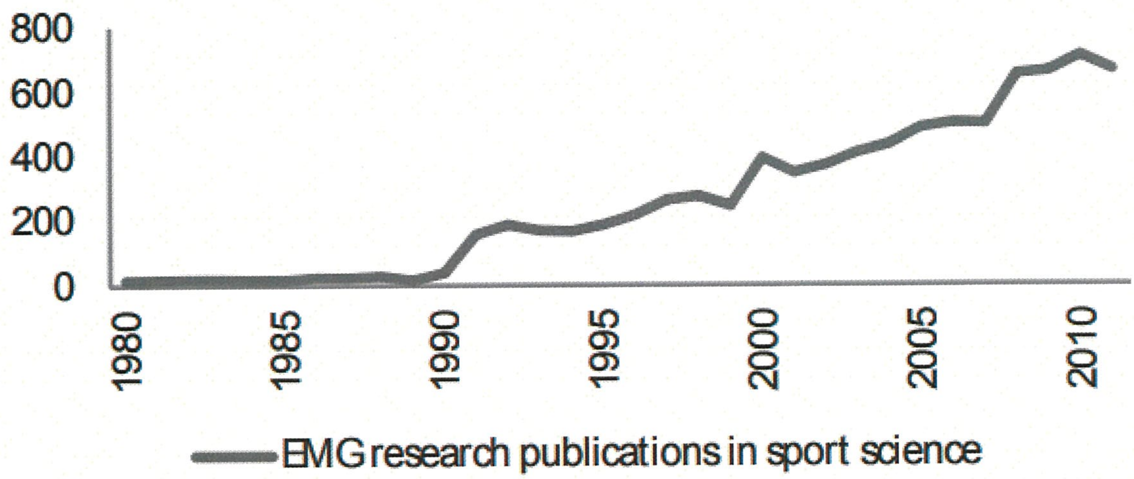

Figure 2-3. The number of EMG publication related to sport science since 1980 [54].

In sports applications, EMGs are usually investigated to assess the quality of the corresponding movement while performing a task. The activation of muscles in an economical way could produce smoother movements, prevent injuries, and provide a reference methodology for training novices. One of the methods to evaluate the effectiveness of movement is evaluating the co-activation at a specific joint while performing the corresponding task. Investigators of neuromuscular science have examined the phenomenon to evaluate stability [57-58] in jump task, or inter-group difference in tennis players [59]. In training, a visual EMG-based system was proposed to train the basketball dribbling movement for novices [56]. In the system, by observation EMG patterns of experts, novice players would improve the dribbling basketball movement.

Furthermore, more and more studies have investigated muscle synergy [60-62] to clarify that whether the Central Nervous System (CNS) recruits and controls small groups of muscles instead of numerous individual muscles to solve the redundancy problem in the motor control, as stated in the hypothesis proposed by Bernstein [13]. Elucidating how the CNS controls these "modules" in sophisticated skills in sports could contribute to validate the hypothesis, as well as improve the performance.

2.2 Kinematics in goal-oriented sports

2.2.1 The time of release

Dart-throwing motion of the wrist, the ability to grasp and throw an object to defend and hunt, has been considered as an advantage in the early stage [63-64] of human beings during evaluations. The motion of the wrist has been investigated in several studies for clinical and sports sciences [65-68] to improve the quality of the joint. In sports requiring extreme accuracy and consistent outcomes like dart throwing or basketball at the professional level, controlling the coordination of several factors of the arm is the primary skill to be an expert. Therefore, it is appealing to understand underlying mechanisms in the motor system of experienced throwers to provide practical guides for coaching and training novices. In this study, dart throwing is chosen since it is a typical throwing with main compound joint movements on the upper limb, thus relatively simple as compared to other throwing tasks requires the coordination of several human segmentations (trunk, lower and upper limbs) such as basketball or baseball. Additionally, the task is easy to evaluate the performance on the dartboard. There are numerous factors could contribute to the performance such as kinds of focus (external and internal) [69-70], psychology [71], and stability of the end-effector by uncontrolled manifold hypothesis [72-73], but the current study focuses on the kinematic factors before/at the time of release, which might be more intuitive to reveal motor strategies of skilled dart throwers.

In any throwing movement, the initial values of position, speed, and direction of the projectile at the time of release provided by the angular kinematics of main articulations of the upper limb (shoulder, elbow, and wrist) directly determine the accuracy of a throw. As a result, timing precision is one of the most critical factors contributing to the accuracy of a throw because if we release the projectile later or sooner, the final position becomes lower or higher, respectively (Figure 2-4, [3]).

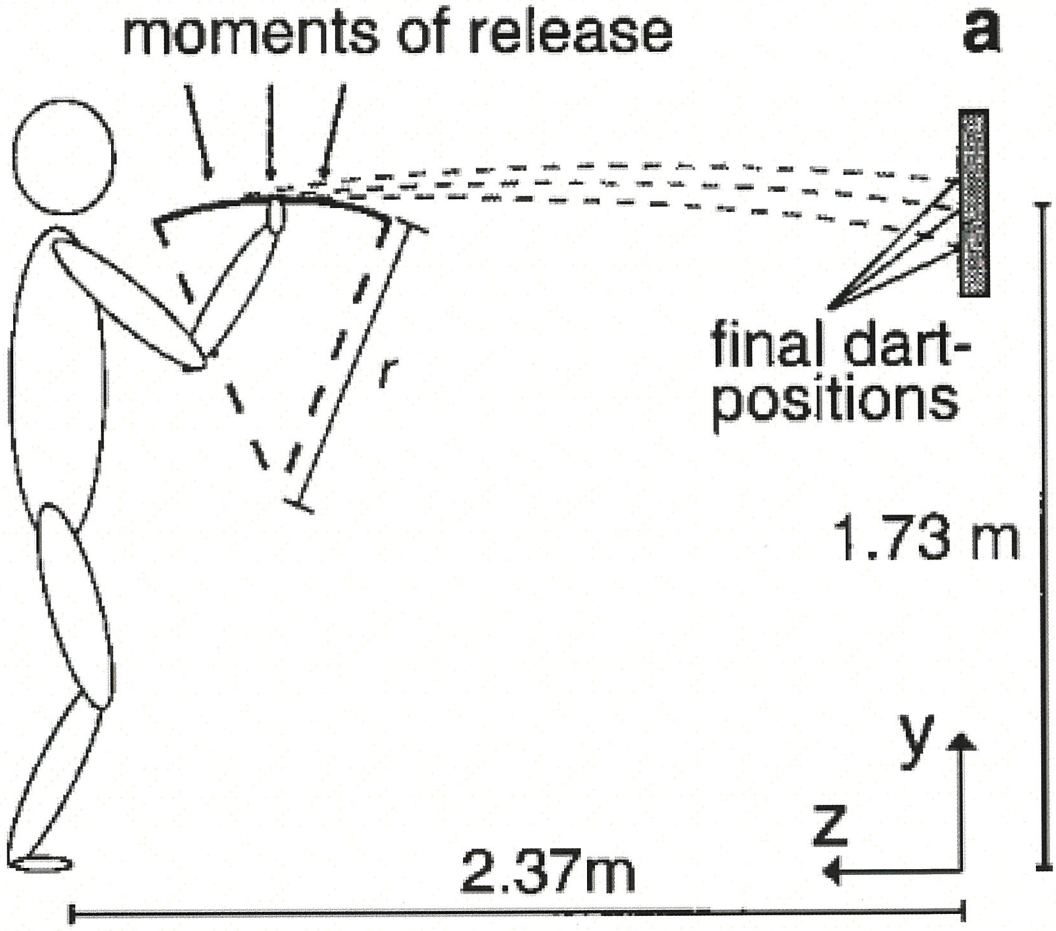

Figure 2-4. Side view of a subject throwing darts [3].

To obtain accurate throws, the kinematic parameters of human joints and the profile of the dart (location, speed, and direction) have to be well-coordinated. However, several studies of throwing movement have *separately* investigated the influence of either kinematics of joint movements or the projectile at the time of release on the performance. I will review the effects of the two following kinematic parameters on the outcome: 1) release parameters of human joints; 2) release parameters of the projectile.

2.2.2 Effects of release parameters of human joints on the outcome

With regard to the kinematics of human joints at the time of release on the outcome, I show the findings in various throwing tasks require accurate outcomes in previous studies.
In ball throwing task, by using magnetic-field search-coil technique to measure kinematic parameters, and detecting the time of release by micro-switches on the middle finger, Hore et al. found that the onset time of finger extension [4] or the variability of the time of release [2] highly affected the performance in ball throwing. Moreover, these authors also suggested that skilled throwers could adjust force appropriately to correct errors in hand acceleration to obtain ball accuracy [5].

In basketball free throwing, a task which is similar to dart throwing, Verhoeven et al. [6] found that releasing balls closer to the moment at which the center-of-mass reached peak height was considered a skill of experienced players. Moreover, the shoulder, elbow, wrist, fingers, and the ball should be kept stable at the same plane while moving before/at the time of release to increase the accuracy [7]. In addition, in an investigation of differences between experienced and novice players, Hung et al. confirmed that experts utilized less elbow and knee-bend, although the release parameter of the ball was similar [8] between two groups.

In the javelin, the angular speed of the shoulder girdle and forearm had a high correlation with the measured distance [9]. Also, Toffan et al. [10] indicated that the position of the back foot at the time of release had a strong effect on throwing the test score in football-quarterback throwing. Furthermore, in dart throwing, skilled throwers slowly moved the backhand before acceleration [11], and release the dart at the moment just before the peak of the elbow angular velocity [12] (see Figure 2-5).

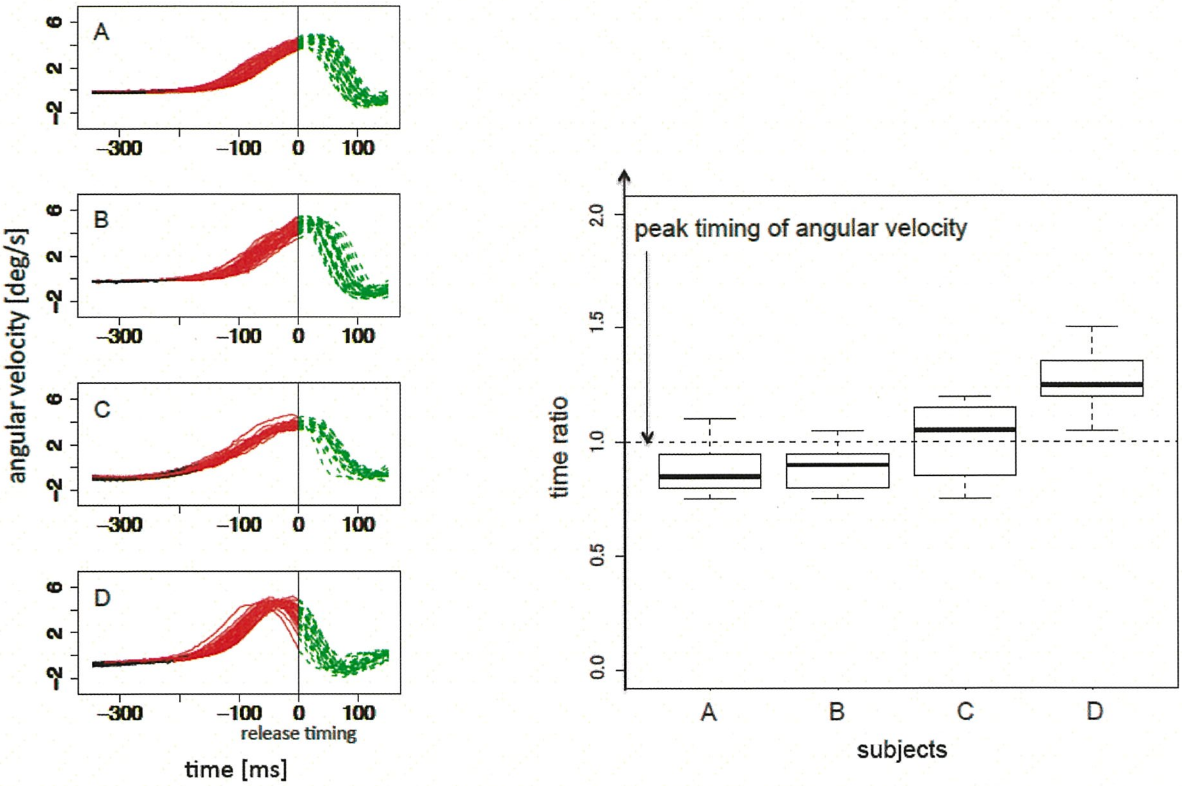

Figure 2-5 Left: Elbow joint angular velocities aligned at release timing. Right: Distribution of release timings aligned at peak of elbow joint angular velocity [12].

However, it is insufficient to evaluate only one release parameter due to the redundancy problem [13]. In addition, variance in one parameter of a joint could be compensated for by variance in a parameter of another joint to achieve accurate throws [14]. Importantly, even though kinematic patterns of human joints at the time of release can be considered as an indicator to classify levels of throwers [8-9,14,76], the relationship between those factors and strategies among experts is still ambiguous.

2.2.3 Effects of release parameters of a projectile on the outcome

Considering the projectile's parameters, in some studies investigating throwing tasks such as javelin or boccia, [9,74,77-78] the release speed individually affects the outcome. However, since the distance is the key performance indicator, the release parameter can solely affect.

On the other hand, in goal-oriented throwing sports, various combinations of position, speed, and direction could lead to the same final position. For example, in free throws of basketball (Figure 2-6), if a player releases the ball at high speed, the corresponding angle (release direction) should be relatively small, and vice versa. In other words, there is a tradeoff to obtain accuracy. Various studies have investigated the ball trajectory to suggest the ideal release conditions in free throws [8,79-82]. There was a suggestion that the release angle of the ball should be 58 to 6.25 degrees to the horizontal plane, and the release speed should range from 23.69 to 24.93 ft/sec, with the release height at 6.72 ft [82], but Kudo et al. [15] suggested that these parameters could co-vary, or compensate for another parameter without influencing the outcome in ball throwing movement.

From the above-mentioned points, release parameters could not be examined individually in throwing tasks.

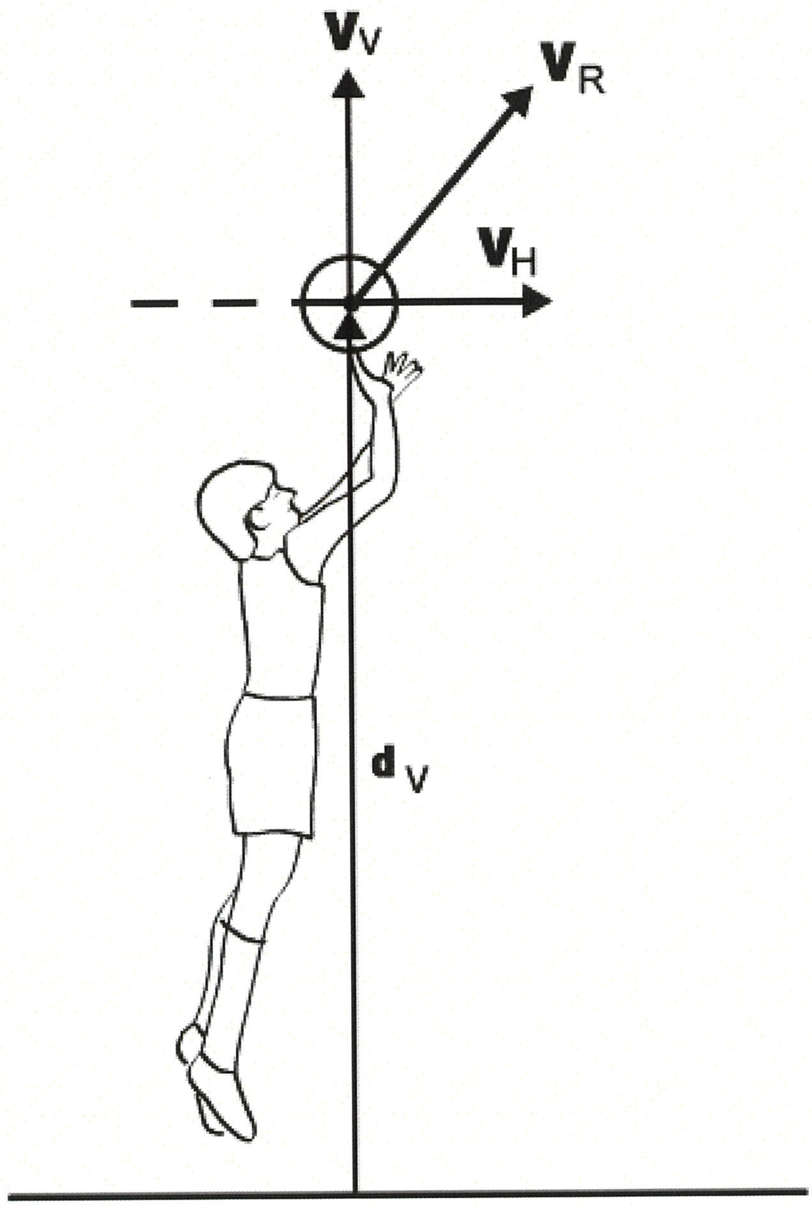

Figure 2-6. The three variables that determine the release parameters of a projectile in two-dimensions: height of release, and the horizontal and vertical velocities of release [1].

2.2.4 Timing sensitivity analysis in throwing tasks

Timing sensitivity could be considered as the relationship between the release time and the resultant final position. Several studies utilized prediction models based on the hand trajectory to predict the final position of a projectile [3,16-19] to investigate the expertise. In these practical and virtual tasks, the hand was assumed to move precisely as the projectile does at the time of release.

Smeets et al. [3] determined the timing sensitivity through the movement of the thumb's kinematics and found that better performance is not a result of trajectory adjustments, which reduce the timing sensitivity of release. The investigators predicted the final position by a model based on a circular path of the hand. However, the estimated error (the difference between the predicted position and the actual position on the dartboard) was systemically too large (20 cm). Therefore, it could be more precise if the projectile trajectory is captured directly and use it to predict the outcome. Moreover, this method also helps to reduce the complexity of mathematics since the circular path is unnecessary.

Cohen et al. [16] proposed an approach that calculates an error curve derived from the hand trajectory in a virtual throwing task. Skilled throwers improved the timing accuracy after practice, with the timing error plateaued at 9 ms after 6 days. After the 6th day of practice, the experts changed their hand trajectory to exploit the redundancy of the task, i.e., increasing the time-window for the successful release to compensate for the limiting timing error. Figure 2-7 shows the trajectory in the execution space of three experienced subjects derived from release velocity and angle of the hand. As can be seen, the trajectories became consistently at the end of practice (Day 15), also made the crossing area with the hit zone larger. However, it is noticed that the task was conducted virtually, which differed from a real throwing task with many degrees of freedom and constraints.

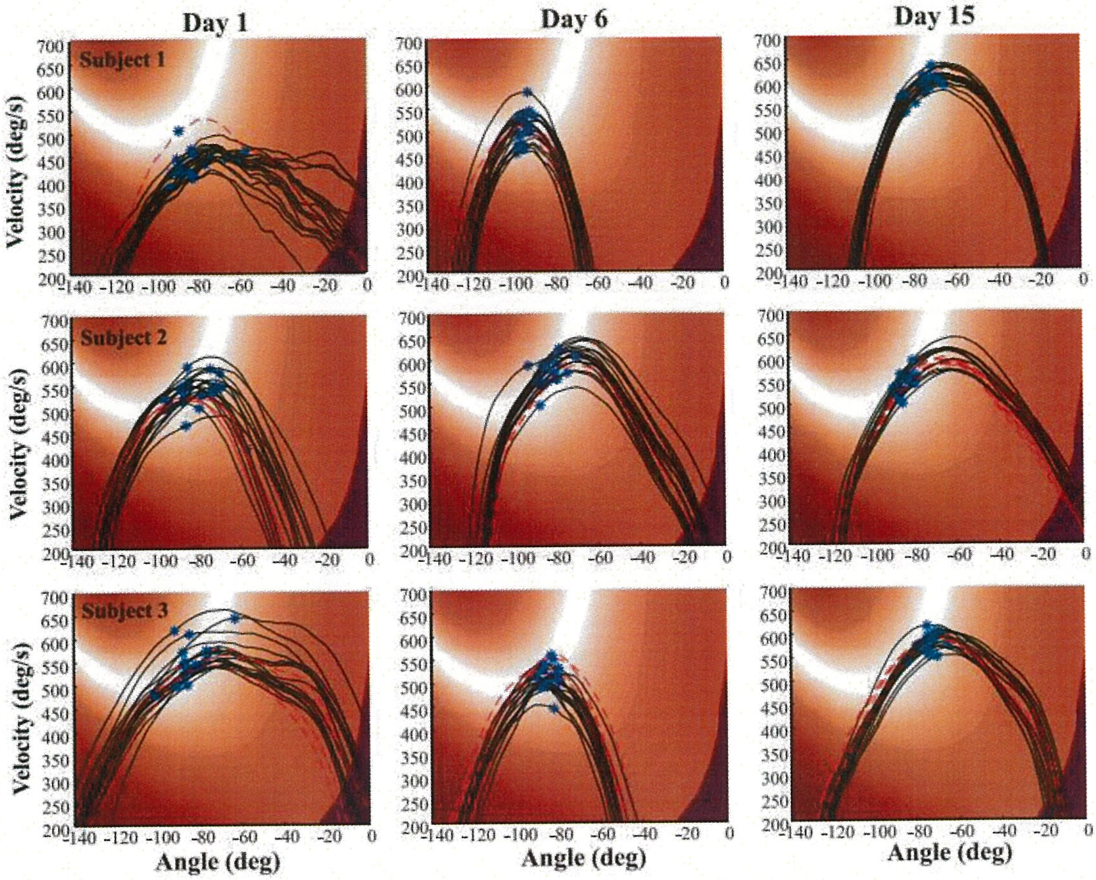

Figure 2-7. Exemplary trajectories in execution space of 3 subjects. For 3 subjects in the expert group, 20 trajectories from 3 selected days (days 1, 6, and 15) are shown. The 20 trajectories are from the middle block. The blue asterisks denote the time of releases. Trajectories for throws that resulted in a target hit are shown in red; those that did not are shown in black [16].

Using a similar method, Nasu et al. [17] investigated the timing sensitivity of dart throwers with different skill levels. Based on error curves derived from the index finger trajectory, it was confirmed that the experts exploited the two strategies, i.e., reducing timing sensitivity and reducing timing error. To quantitatively evaluate these two temporal factors, the authors utilized two indexes from the index trajectory (Figure 2-8A): time successful zone (TSZ) and timing error (Et). TSZ was defined as the amount of time in which every release moment would result in accurate throwing, or the error curve was in the success zone (the horizontal green shade in Figure 2-8B). The latter was calculated by the absolute timing difference between the actual release and "optimal release", where the corresponding vertical error equals zero (Figure 2-8B). The salient point of this approach is that there were two TSZs in some throws. The timing difference between the TSZs occasionally was large (e.g., about 25 ms in Figure 2-8C), which might be unnecessary to accumulate the total TSZ. Moreover, in some specific cases, there were two optimal release moments, which could be redundant, even though only the one closer to the actual release was calculated. The results showed that experts who had less timing accuracy (large error timing) using longer TSZs characterized by a complementary hand trajectory to compensate. On the other hand, experts who had shorter TSZ reduced variability in the release times to obtain smaller Et, or the dart was released very closely to the "optimal release". However, the prediction model might be imprecise because of the discrepancy between trajectories of the index tip and dart during the acceleration phase of a throw. Indeed, when the hand moves closer to the time of release, the two trajectories become different since the index tip starts to move laterally to release, whereas the dart continues to go straight forward. Furthermore, since the relative position between the index finger and a dart is dependent on gripping ways, this prediction model cannot be generalized for all subjects. As a result, a model estimates the vertical error based on the measured trajectory of the projectile, thus it should be more precise, and more intuitive if there is only one optimal release and TSZ.

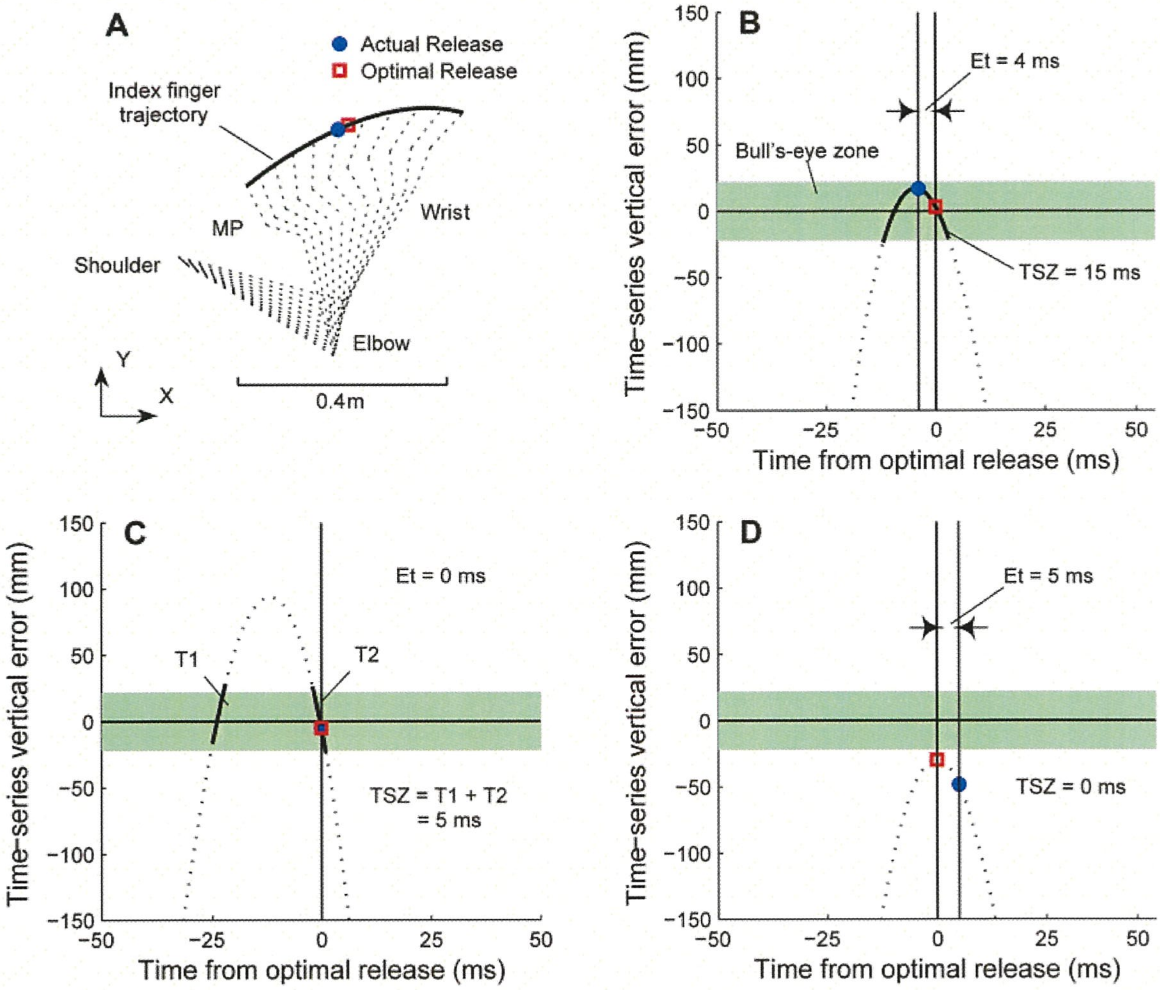

Figure 2-8. Example of time-series vertical error curves and definitions of relevant variable. A: Shown is an example of the index finger trajectory, from the side-view during a period extending 50 ms before and after the actual release. The dashed line indicates a stick figure of the throwing arm at 10-ms intervals. The coordinate data of the MP, wrist, elbow, and shoulder were only used to draw the stick figure. B–D: A curved line represents the time-series vertical error, which was calculated from the index finger movement (position, velocity, and direction of motion). The horizontal solid line indicates where the vertical error is zero. The horizontal green shade indicates the success zone for the required target. Timing error (Et) was defined as the absolute difference in time between the actual and optimal releases. The time in success zone (TSZ) was defined as the amount of time that the curve was in the success zone, and it is shown with bold black lines. When the curve crosses the zone twice, TSZ is quantified as the sum of two values (C). When the curve does not enter the zone, TSZ is zero; I called this trajectory a "non-hit trajectory" (D) [17].

2.2.5 Hypothesis

From the above overview of release parameters of human joints and projectiles in terms of kinematics, neither human postural control nor the projectile movement at the time of release can represent the overall skills or strategies of individuals. Few known studies investigated the relationship between these parameters and the strategies of skilled throwers. Therefore, this study aims to clarify how experts control the angular kinematics of proximal joints (elbow and wrist), hand trajectory, and projectile's parameters (speed and direction), and connect these factors with throwing skills and strategies in dart throwing. The hypotheses in the kinematic analysis were proposed as follows:

1. Experts who reduce timing sensitivity might pre-plan to move the hand trajectory in an appropriate way related to spatial control before release timing and less focus on timing precision. Meanwhile, the hand path of experts who reduced timing error did not move in that manner.

2. Kinematic parameters from proximal joints (i.e., the angular acceleration of the elbow and wrist) and the dart (release speed and direction) would affect the timing sensitivity, reflecting specific characteristics of each strategy. Therefore, this implies that the strategies are not only characterized by the hand trajectory as reported in previous studies [16,17].

2.3 Electromyography in sports

2.3.1 Co-activation phenomenon during actions

Opposite movements at a human joint (e.g., flexion and extension) are produced at least by two muscles, commonly referred to as the agonist and the antagonist [83]. The agonist is the muscle contracts to supply force to produce an action, while the antagonist opposes the action. Therefore, co-activation of the pair of muscles at a certain joint while moving is associated with increased stiffness of the joint, which prevents the smooth movement. In an economical manner of neuromuscular control, while performing a task in one direction (flexion or extension), the antagonist should be relaxed while agonist is activated. For instance, in eccentric contraction which associated with elbow extension, *Triceps brachii* (agonist) is contracted to extent the arm, and *Biceps brachii* (antagonist) is relaxed; and vice versa (Figure 2-9). Therefore, during a certain movement, if both antagonist and agonist muscles were activated at the same time, it would be considered as a negative factor to obtain the effective movement.

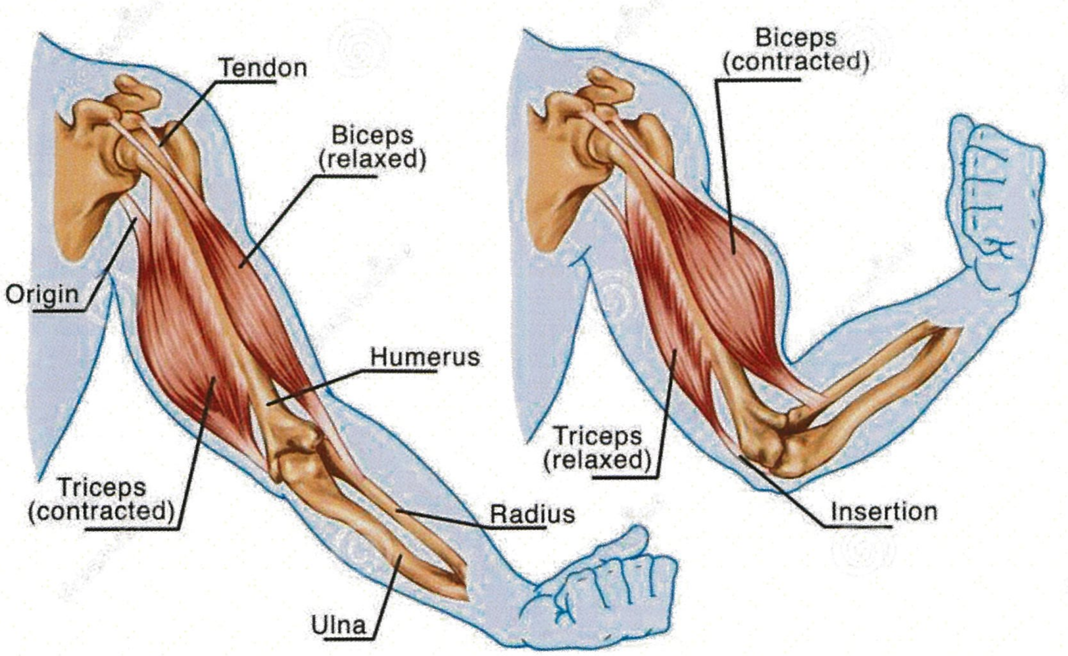

Figure 2-9. Agonist (*Biceps Brachii*) and antagonist (Triceps Brachii) muscles at the elbow joint. If a muscle is activated, the other one is relaxed and vice versa.

There is a hypothesis that decreased activation of the antagonist is an indicator of acquiring motor skills [20]. There have been several studies on skilled subjects demonstrate the hypothesis [59,12,84]. For example, in tennis players, with isokinetic exercises, the antagonist muscle activities in non-player were confirmed to be larger than experts. It means the experienced players have adapted to reduce the activation level of the antagonist muscle after long time practice, to obtain smoother movements at the elbow joint [59]. Similarly,

In dart throwing, *biceps brachii* (BB) and *tricep brachii* (TB) are the key muscles since it helps to drive the forearm forwards during the acceleration phase. In a previous study, Yamaguchi et al. [12] has found that at the time of release, the best performer (expert A in Figure 2-10) showed the ideal muscle activations during throwing with agonist (*BB*) did not activate whereas the antagonist (*TB*) activated just before the time of release. The result implies that experienced throwers had reduced the antagonist activation to obtain a smooth elbow extension. However, as the number of subjects in that study was small (two experts and two beginners), the phenomenon in dart throwing should be carried out with a larger size to support the hypothesis. Also, it is noticed that in a rapid movement at the elbow joint, antagonist muscle (*TB*) would be activated to decelerate the movement [85]. Therefore, this phenomenon should be examined carefully. Thus, a study on inter-group differences of more subjects should be conducted in dart throwing.

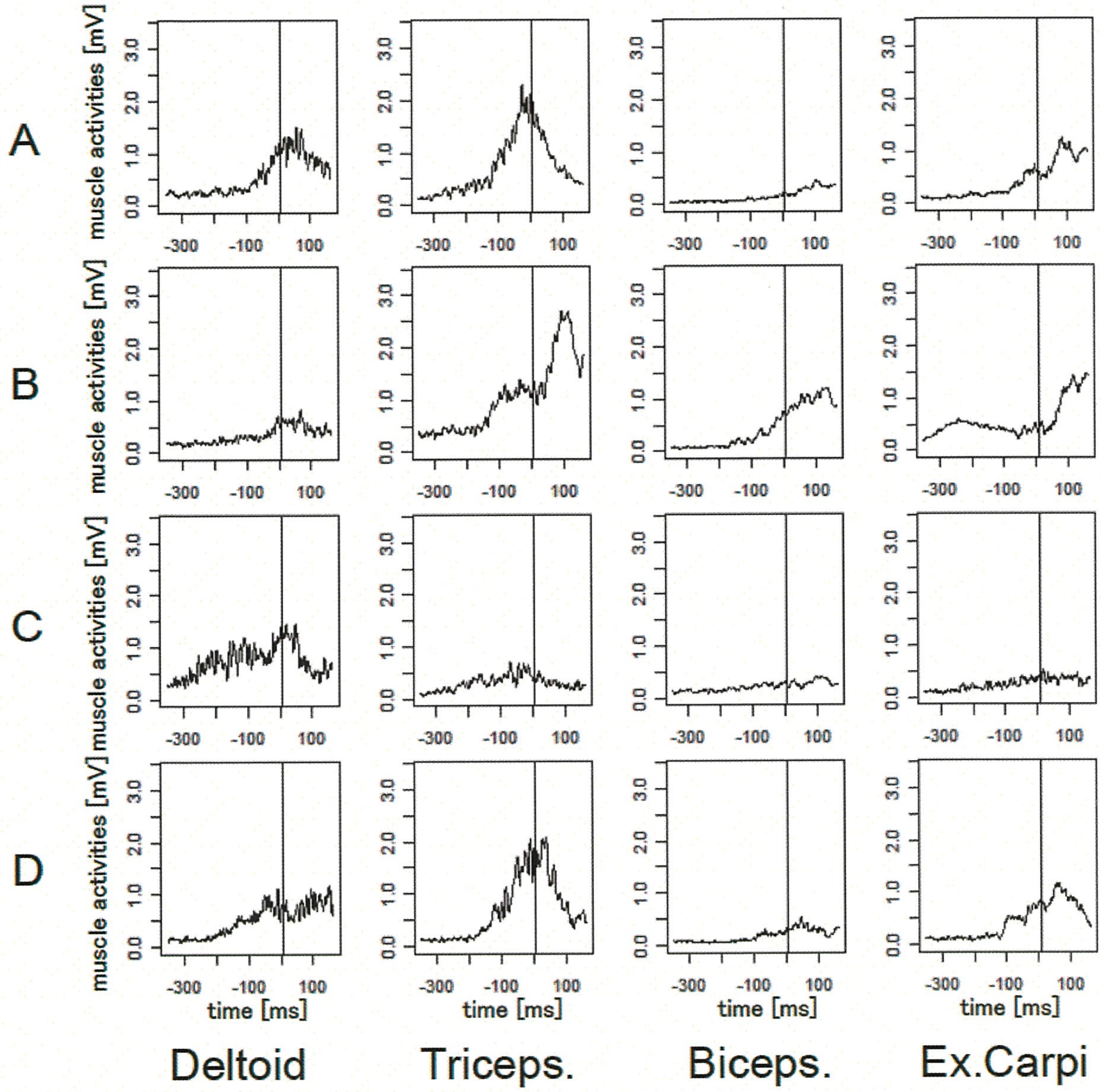

Figure 2-10 Muscle activities (EMG) aligned at release timing [12].

2.3.2 Muscle synergies hypothesis

Muscle synergy analysis has been applied in a wide range of applications, such as throwing in avatar character [86], hand posture classification [87], and clinical [88-89]. In particular, human behaviors (similar to throwing) in daily life such as walking [90], standing-up [91], and fast-reaching [92], as well as sophisticated movements in sports [93-95], were decomposed and explained by a small number of "blocks" (synergies) to provides evidence to the muscle synergy hypothesis. Muscle synergies could be divided into time-varying or synchronous. In synchronous synergies, the non-negative matrix factorization (NNMF) algorithm is used to identify a group of muscles from the observed data. Equation (1) shows the NNMF to extract muscle synergies.

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

M is the recorded EMG data or a matrix with n-dimensional vectors (n recorded muscles). Each row of M(t) represents the observed time-varying of one muscle. W is the n-dimensional weight matrix, with each vector (column) represents the relative activation level of the recorded muscles in the synergy. A synergy (W_i) is combined with the corresponding activation coefficient $c_i(t)$, which determines the time-varying for the synergy in the temporal domain. Figure 2-11 illustrates an example of muscle synergies after applying the NNFM algorithm, three muscle synergies and corresponding activation profiles are extracted from observed EMG signals of 10 individual muscles.

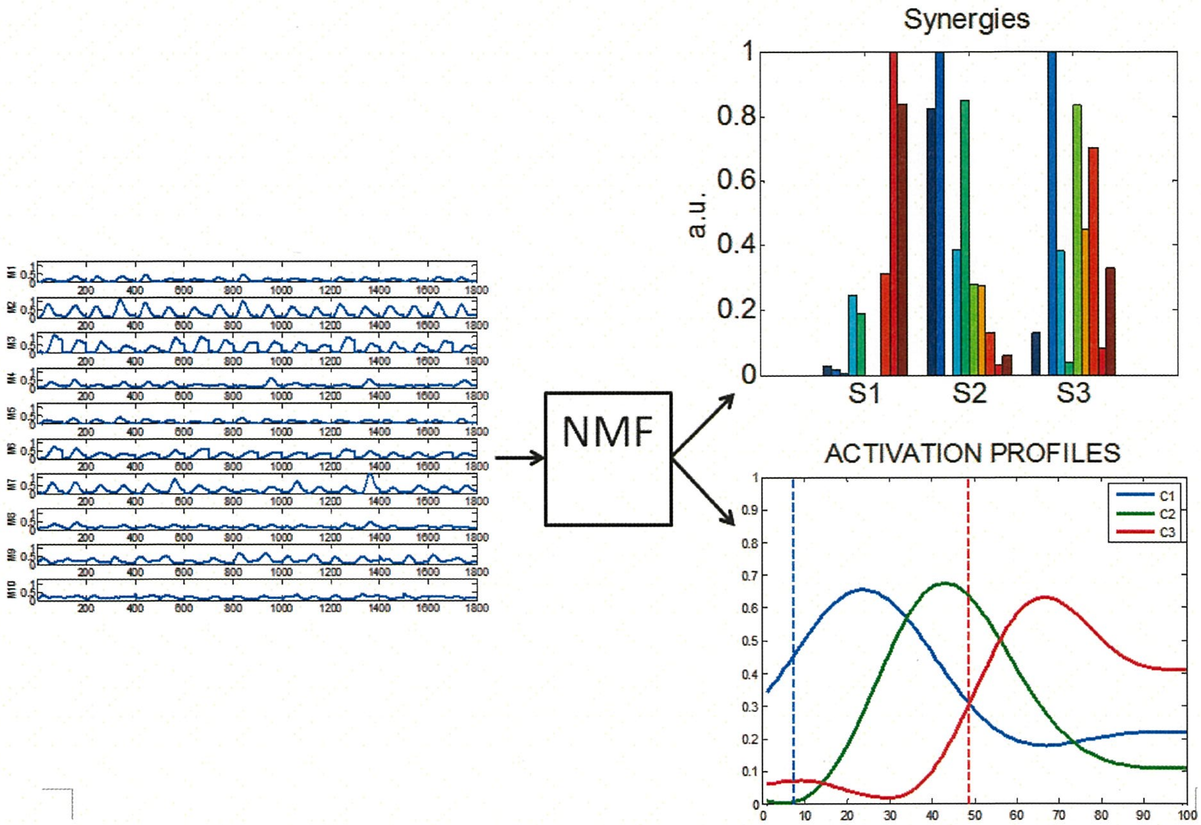

Figure 2-11. An example of muscle synergy extraction after apply NNMF.

Muscle synergies were suggested to be similar across subjects and conditions in previous studies while performing specific tasks such as cycling [94] backward giant swings on the high bar [95]. For example, a set of three muscle synergies account for 93.3 ± 1.6% of the variance explained in observed EMG data of 11 muscles in untrained cyclists. The muscle synergy vectors were confirmed to be consistently robust in the weight matrices, whatever the constrained conditions of torque, torque-velocity, and posture were. Meanwhile, the co-activation coefficients were found to be adapted to respond to changes in torque and posture. Although evidence from a wide range of behaviors has been reported to support the hypothesis, few known studies on muscle synergy in dart throwing movement, which requires the complex coordination of multi joints and associated muscles to obtain accuracy outcome.

To summarize, the author has reviewed the literature related to the current thesis and proposed the hypotheses in kinematics and EMG signals.

In the next two chapters, the author presents the research to investigate skills and EMG signals of experts [96], followed by the analysis of EMGs in dart throwing of beginners and throwers at the intermediate level.

Chapter 3. Analysis on motor strategies of skilled dart players

3.1 Methodology

3.1.1 Experiment

a) Subject and ethics

Eight neurologically healthy and right-handed professional dart players (6 males and 2 females; height: 177.25 ± 9.07 cm) took part in this experiment. Their handedness was confirmed by using the Edinburgh Handedness Inventory [97]. All participants had been competitive players and dart players for an average of 9.0 ± 4.60 years. Their best-recorded scores in a count-up game ranged from 1083 to 1210. The maximum score in one count-up game is 1440 (24 throws with a maximum score of 60 for one throw). The subjects were informed about the procedure and provided written informed consent prior to the experiment.

The experimental procedures were approved by the ethics committee of the Tokyo University of Agriculture and Technology.

b) Experimental setup

In this experiment, hard darts (steel tip) were utilized, and all subjects confirmed that they could adapt to the darts. The center-of-mass (COM) was determined beforehand. Subjects were asked to stand in front of the throwing line (237 cm away from the dartboard) and aimed for the bull's-eye (center of the dartboard), which is 172 cm off the ground.

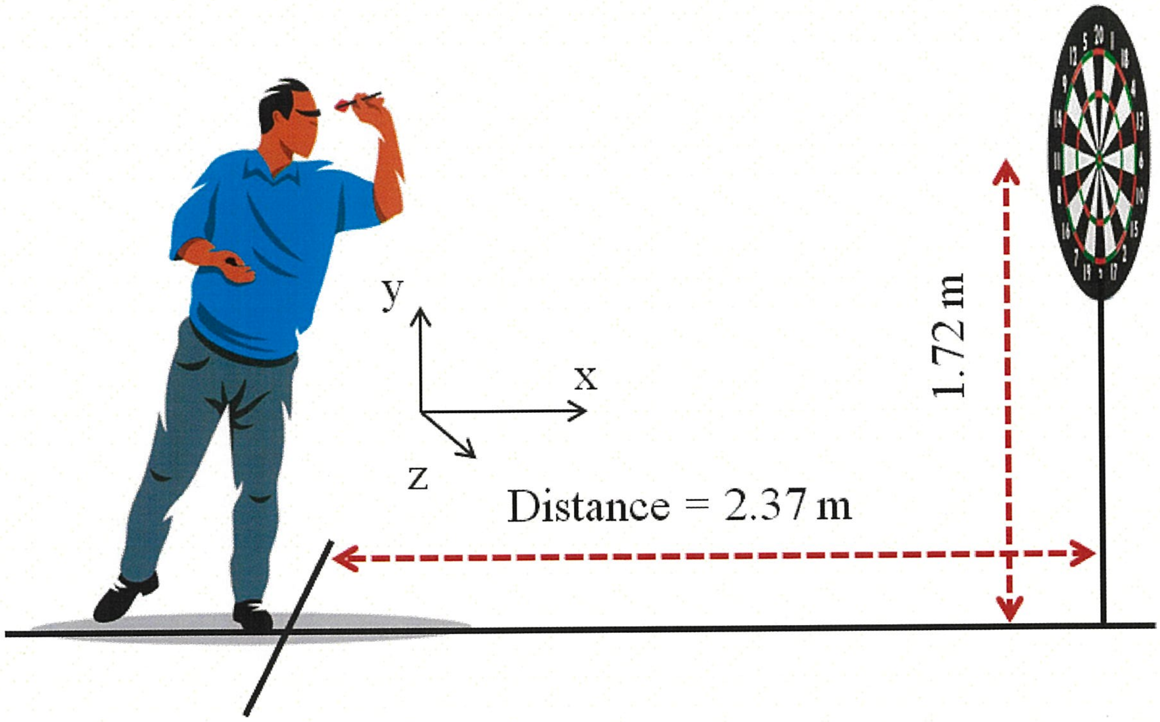

Figure 3-1. The gereral set up of the experiment.

Six infrared cameras (Prime 13, Optitrack, Inc.) were used for motion capturing and used one of these cameras in MJPEG mode to detect an LED light for trigger (explained below) and record the throwing motion. All cameras were synchronized by a hub and located appropriately, so they could capture movements of the subject while throwing and the movements and trajectory of the dart during the flight (Figure 3-2). The workspace was calibrated and adjusted before the experiment. The overall re-projection error of the calibration was 0.82 ± 0.02 mm. After that, a coordinate system for the experiment was set up.

For EMG recording, we used the WEB-5000 system (Nihon-Kohden, Japan). Muscle activities of subjects were recorded by a wireless device ("WF" in Figure 3-2) connected to eight surface electrodes attached on eight muscles along the arm. The WF was tightly put on the belt of subjects and transferred EMG data to a telemeter. Afterward, the EMG data from the telemeter was feed to the PC through a data acquisition device (NI-USB 6218 BNC, "DAQ" in Figure 3-2). Additionally, the data from the motion capture system (kinematics) and a trigger signal from the LED light was fed to the data acquisition device with the same recording rate as EMG data.

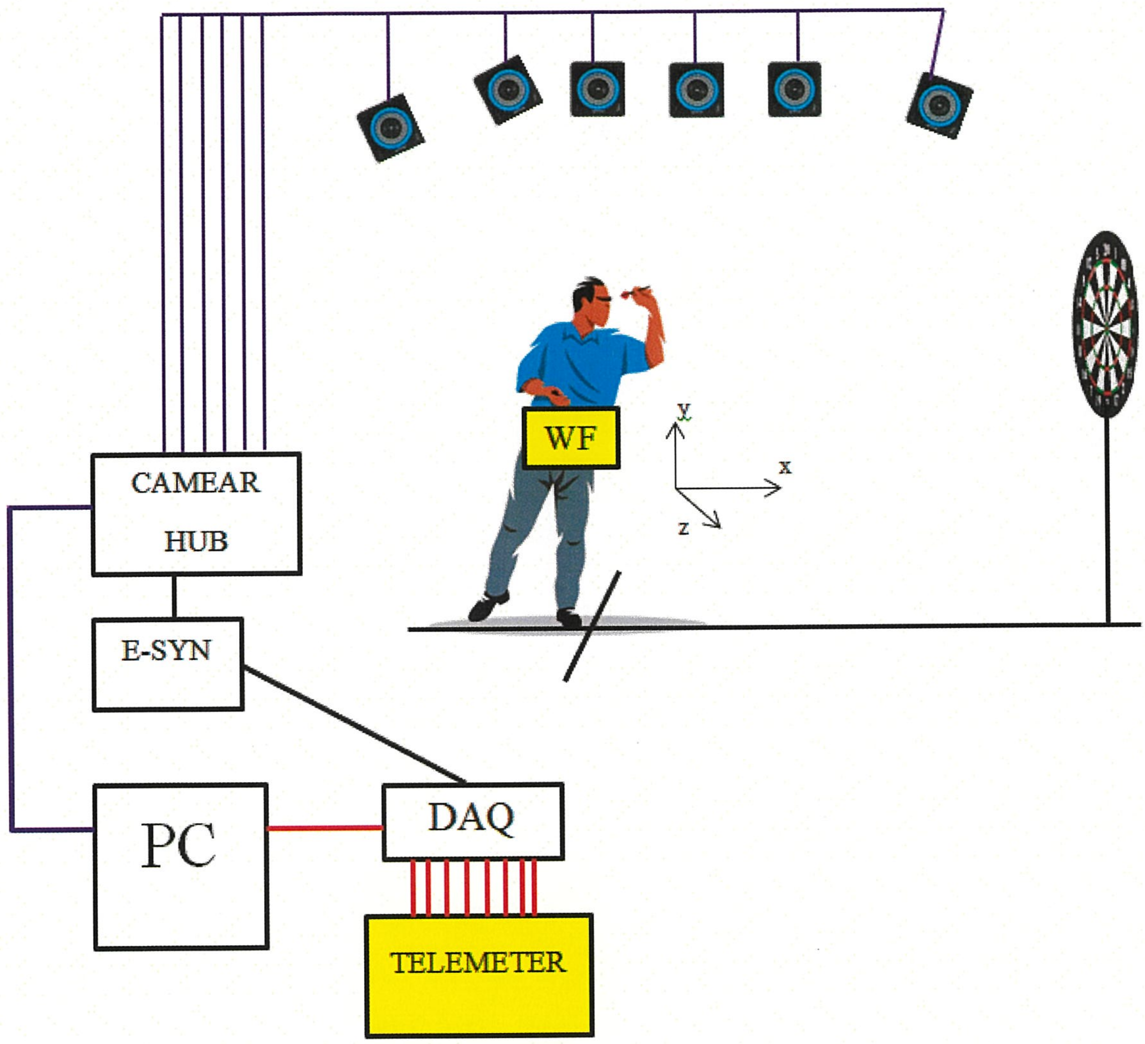

Figure 3-2. Devices used for data recording in the experiment.

c) Procedure

The experiment took approximately an hour and was divided into four stages: *warm up*, *preparation*, *confirmation,* and *throwing*. Throughout the experiment, EMG and kinematic data were recorded per set, which included six throws. After one throw, the dart was taken out of the board immediately to prevent it from being overlapped or hidden by the next dart's final position. Subjects started each set of throwing when given a verbal command by an experimenter.

Warm up stage:

Before the experiment, all subjects were asked to practice for three minutes to get used to the darts, which was followed by a *baseline* session with 18 throws (three sets of six throws). The session was conducted with natural throws without electrodes and markers attached on the throwing arm. Thereafter, subjects were asked to sit so that the experimenter could attach the electrodes and markers for the next stage.

Preparation stage:

Firstly, the skin of subjects was cleaned by alcohol tissues and shaved to reduce the resistance, and then the experimenter attached surface electrodes on 8 muscles along the throwing arm: *flexor pollicis longus, brachioradialis, flexor carpi radialis, flexor carpi ulnaris, biceps brachii, triceps brachii lateral head, triceps brachii long head, anterior deltoid.* Muscle activations of subjects were recorded by a wireless device connected to a telemeter. These EMG data were transferred to the data acquisition device.

For tracking the movements of the trunk, shoulder, elbow, and wrist joints, we attached four hemispherical facial markers (M markers in Figure 3-3 and Figure 3-4) on the corresponding anatomical landmarks: *7^{th} rib*, *acromion process*, *medial epicondyle,* and *distal radioulnar joint*. A smaller marker (d = 4 mm) was attached on the proximal interphalangeal joint of the thumb (referred to as *M1* in Figure 3-3 and Figure 3-4).

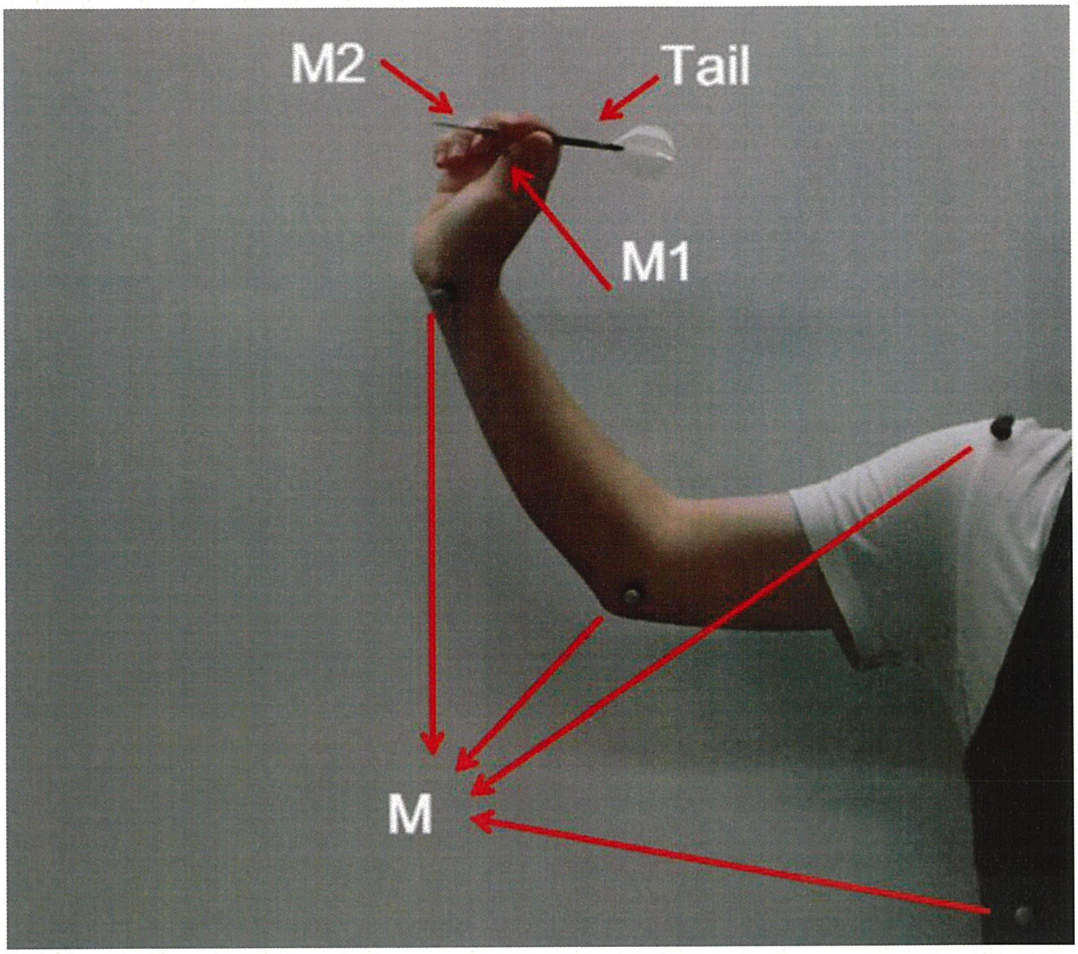

Figure 3-3. Markers attached on human joints in this experiment.

Moreover, we utilized two reflective tapes attached on darts to capture the dart movement. The first tape was wrapped around the dart's tip and was 20 mm away from the COM (near the dart tip) to create a marker (M2), and the second one was attached on the bottom of the dart shaft ("*Tail*" in Figure 3-3A and Figure 3-3B). We assumed that the dart's final position was the same as the position of marker M2.

EMG and kinematic data were recorded at 2000 Hz and 200 Hz, respectively, and we synchronized the two kinds of data by the trigger signal. Namely, the moment (frame) at which the LED light changed from OFF to ON, as observed by the camera in MJPEG mode, was synchronized with the sample of the trigger signal when it changed from high voltage to low voltage.

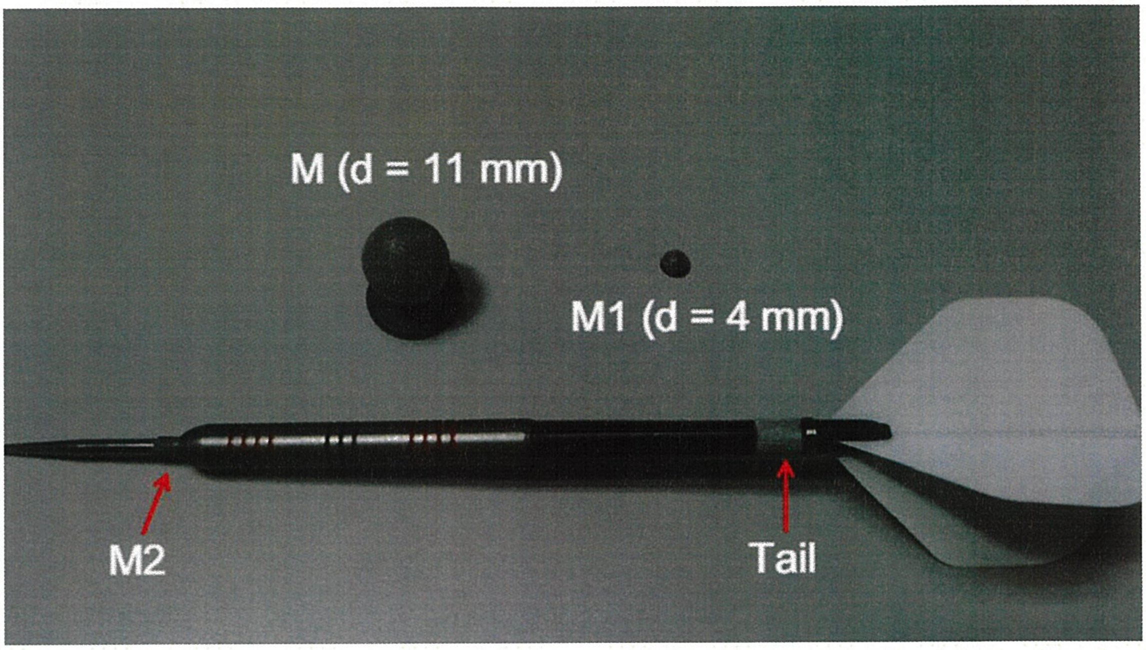

Figure 3-4. Markers attached on the dart.

Confirmation stage:

After wearing EMG electrodes and attaching the markers (described above), subjects were asked to perform 18 throws (three sets of six throws) in a post session to confirm whether discomfort or any other inconvenience affected their performance, and confirm the validity of electrode positions. To evaluate the effect, we compared the performance differences between the baseline and post sessions (see "Performance evaluation", 3.1.4 section).

Throwing stage:

Subjects performed 42 throws (seven sets of six throws). In this chapter, only kinematic data of these seven sets were analyzed.

3.1.2 Data processing

All kinematic data of the human arm and dart were low-pass filtered at 20 Hz, using a zero-phase-lag 2nd-order Butterworth filter. After detecting the time of release (see "Detecting the time of release", 3.1.3 section), to obtain the precision of 1 ms and make the data more easily comparable to data reported in previous studies [16,17], we interpolated the data into 1000 Hz using a cubic spline interpolation.

3.1.3 Detecting the time of release

Since the distance between the thumb and dart tip was almost unchanged during the throwing period and suddenly increased at the time of release, we determined the time of release by the two following conditions. First, the time of release was detected when the Euclidean distance between markers M1 and M2 at this moment exceeded a threshold, which was set to the maximum distance measured within the first 150 ms when subjects started to cock back the forearm. Second, the difference between the two distances at the next two frames (5 ms) after the moment detected by the first condition was larger than 25 mm. The second condition ensured that the dart was released because, in rare cases, the distance slightly fluctuated (up and down) around the threshold when the arm moved in the acceleration phase, which leads to false detections. We also utilized the camera data recorded in MJPEG mode to check the time of release.

In EMG analysis, after synchronization by the trigger signal (see "Experiment", section 3.1.1c), raw data were high-pass filtered at 20 Hz [41], using a zero-phase-lag 2nd-order Butterworth filters.

We used MATLAB (Mathworks Inc.) to perform all kinds of data processing and statistical test.

3.1.4 Performance evaluation

To evaluate the performance, first, the target coordinates were determined in the coordinate system. Before the experiment, the experimenter put a hemisphere facial marker (d = 4 mm) on the center of the bull's-eye of the board and measured its location (referred to as *target* position). Afterward, we removed the marker. During the experiment, after a throw, we measured the final dart's position by marker M2 on the dartboard. The vertical errors of the throw were calculated by taking the difference between the two positions in the vertical plane, i.e., *target* position and marker M2 on the board ("y_{TG}" and "y_{dart}" in Figure 3-5, respectively). Regarding movement in the horizontal plane of the movement (y and z coordinates, see Figure 3-2), the dart's final position is only determined by its initial position and release direction since no forces are acting upon the dart after the time of release [3]. Due to the simple linear relationship in controlling horizontal error on the board (z coordinate in Figure 2-2), which is independent of the dart release speed, this thesis only focuses on the vertical error on the board, which is involved in the movement in the sagittal plane (x and y coordinates in Figure 2-2).

In this experiment, successful throwing was defined that the resultant dart position is within the bull (i.e., the outer circle of bull's eye with 16 mm radius). In other words, a throw was considered successful if the absolute vertical error was less than 16 mm ($|y_{dart} - y_{TG}| <$ 16 mm, see Figure 3-5). We evaluated the performance of the experts by the absolute vertical error and the success rate (out of 42 throws). Figure 3-5 shows an example of the method to calculate the vertical error.

To check whether the discomfort due to the electrodes influenced the performance on the board, we used the Student t-test to evaluate the difference of the absolute of the vertical error between the *baseline* (18 throws) and *post* sessions (18 throws) within a subject.

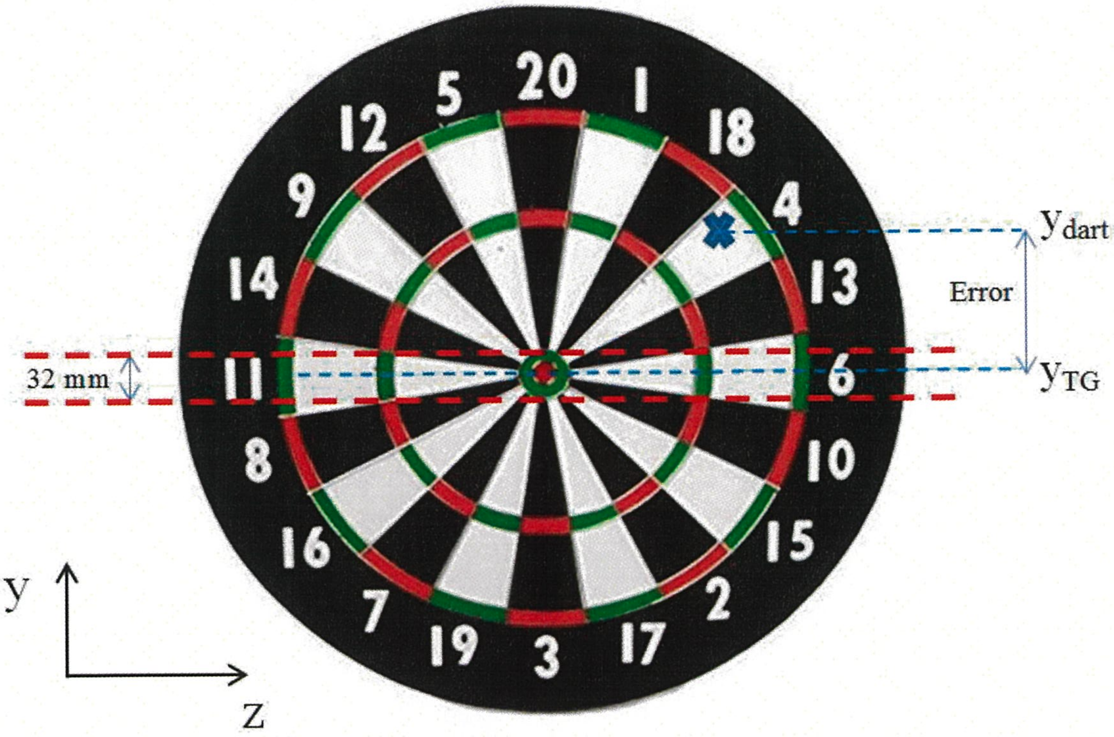

Figure 3-5. An example of calculating the vertical error of a throw. The "x" marker represents the final position of the dart measured by the capture system. The vertical error ("Error" in the Figure) is calculated by the difference between the dart's final position (y_{dart}) and the target position (y_{TG}). A throw would be considered as successful if the absolute vertical error was less than 16 mm relative to the y_{TG}, or the dart landed at any positions within the zone (32 mm in length) restricted by the two dashed red lines.

3.1.5 Time series of vertical error based on dart tip movement

We assume that the COM of the dart moved exactly the same as that of marker M2 at the time of release and then flew with a parabolic trajectory after the moment, neglecting air resistance and rotation. Vertical error at time t was calculated according to equation 2 [16,17]:

$$Ey_t = \left(y_t + \tan\theta_t \times (x_{TG} - x_t) - \frac{9.8}{2} \times \frac{(x_{TG}-x_t)^2}{(v_t \times \cos\theta_t)^2}\right) - y_{TG} \quad (2)$$

where x_{TG} and y_{TG} are the horizontal and vertical coordinates of the target position in the sagittal plane, respectively; x_t and y_t are horizontal and vertical coordinates of the dart in the sagittal plane at time t, respectively (see Figure 3-2); v_t, and θ_t are the speed, and direction of the dart (magnitude and angle of the dart-release vector, respectively, see an example in Figure 3-6) at time t, respectively. Figure 3-6 shows an illustration of how to calculate a vertical error from the parameters of the dart (x_R, y_R, θ_R, and v_R) at the corresponding time of release.

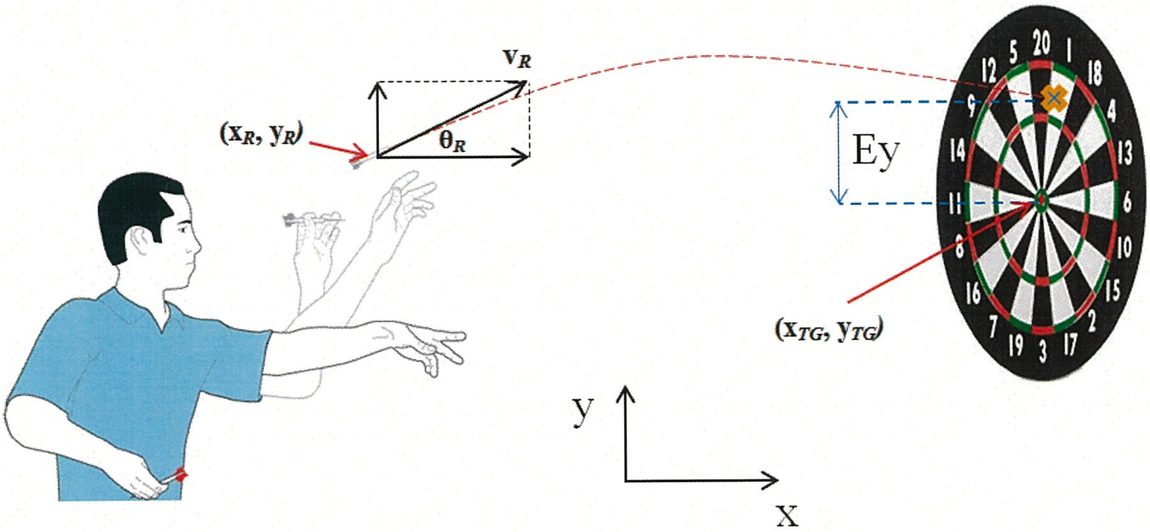

Figure 3-6. The illustration of in a throw and the vertical error calculated by parameters at the time of release. The "x" marker represents the estimated final position of the dart. x_{TG} and y_{TG} are the horizontal and vertical coordinates of the target position in the sagittal plane, respectively. x_R, y_R, θ_R, and v_R are the horizontal and vertical coordinates in the sagittal plane, speed and direction of the dart at the time of release, respectively.

There was always an estimated error (offset) between the calculated location and the final location of the dart measured by the motion capture system. To eliminate the estimated error, in each throw, we shifted the curve by adding or subtracting the offset value. In other words, for practicality, the calculated value after offset corrections at the time of release in the error curve was the same as the actual error on the board measured by the motion capture system.

In this study, since the actual impact position of a dart on the board was measured by the motion capture system together with the calculated position (before offset corrections), we evaluated this prediction model by the following indices: (1) the absolute of the estimated error, (2) the average of correlations between the actual and calculated positions across all experts, and (3) the correlation between the standard deviations of the actual error (measured by the motion capture system) and calculated error among all experts.

We also calculated the vertical error curve derived from the thumb movement by the same equation with the dart, but with the kinematic parameters of marker M1 at time t. The vertical error curve derived from the thumb was not calculated to predict the actual final position of the dart on the board because of a large estimated error [3]. Instead, it was used to investigate the relationship between the thumb and dart trajectories temporally and spatially. Moreover, a Wilcoxon signed-rank test was conducted to assess the difference between the estimated errors calculated from dart marker (M2) and finger marker (M1) trajectories to confirm that the model based on the former can estimate the final position more precise. Figure 3-7 shows movements of the throwing arm (stick figures represent in red lines) and dart trajectory (red curve) during a successful throw.

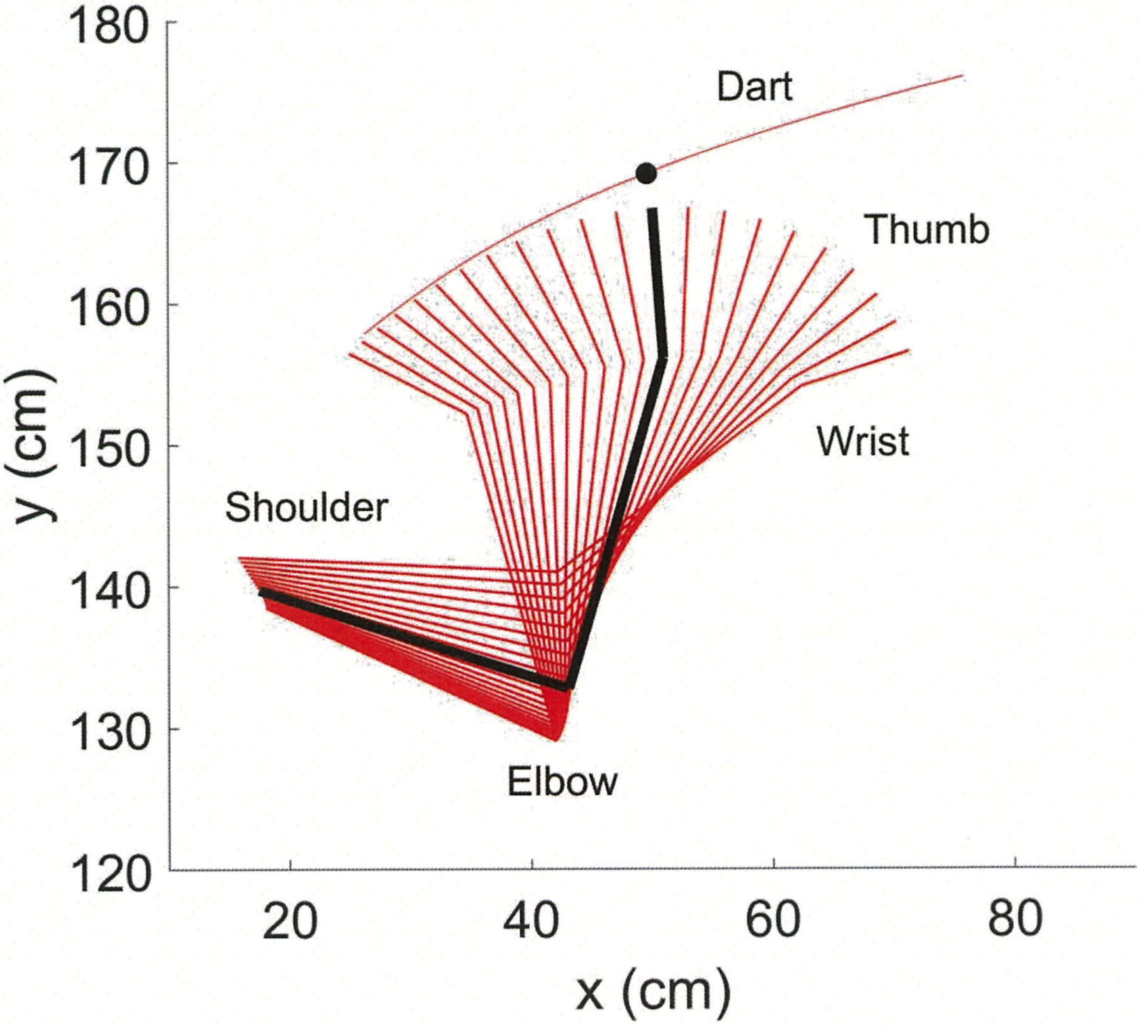

Figure 3-7. An example of a throw displayed in the capture system. An example of the coordinate data in the sagittal plane of the dart trajectory and human joints recorded during a throw (105-ms time-window started from 60 ms before the time of release, at 5-ms intervals). The red curve represents the dart trajectory. The red line describes a segment between two joints, and every three connected red lines indicate the position of the throwing arm at a certain time. The thick black lines and black round marker describe the position of the throwing arm and the dart position at the time of release, respectively.

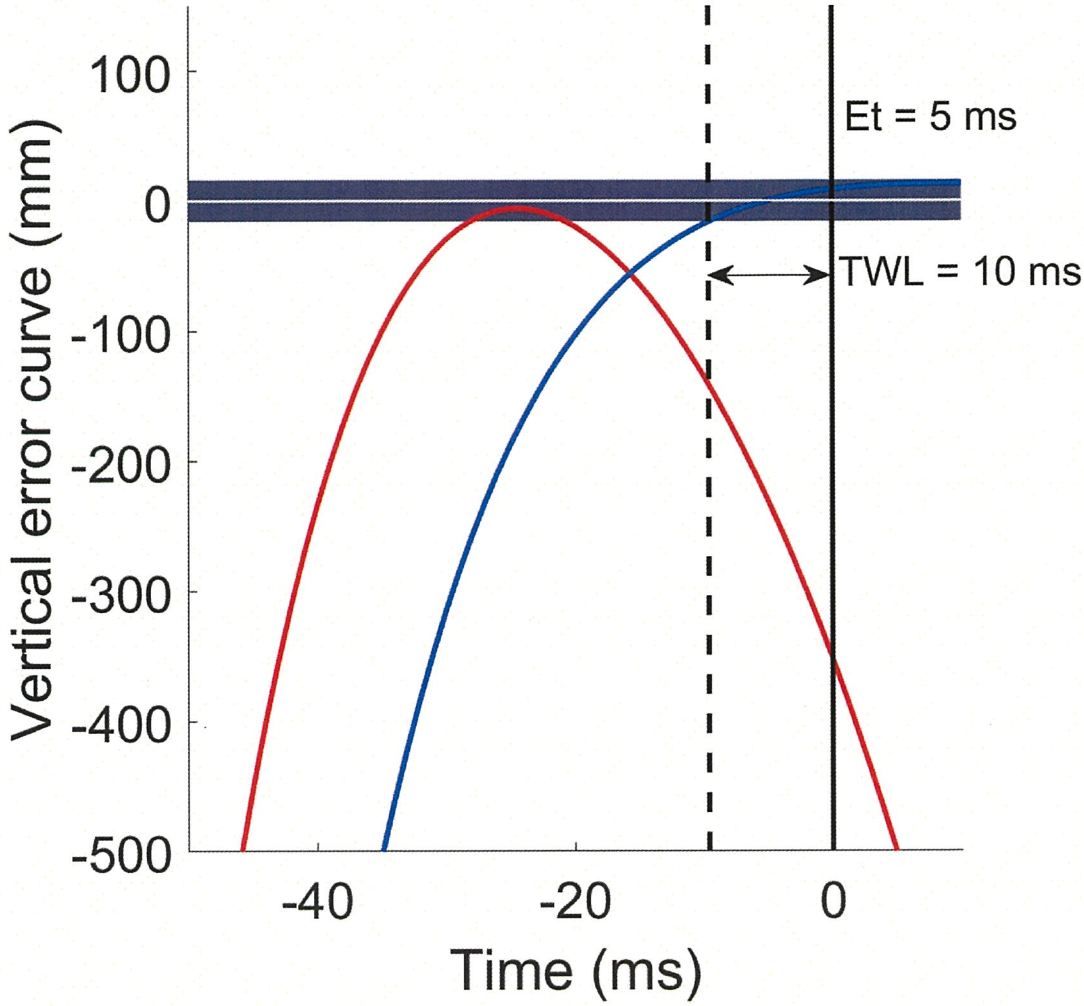

Figure 3-8. Vertical error curve derived from the thumb and dart movement for a single throw. Vertical error curves were derived from the thumb (red) and dart (blue) trajectories. The black line represents the time of release. The hit zone and the zero line (optimized error) are represented in the dark gray zone and horizontal white line, respectively. The dashed black line demonstrates the moment that the blue curve crossed the hit zone and the time-window length (TWL) in which the thrower can release for an accurate throw (10 ms in this example). The timing error (Et) is 5 ms, determined by the absolute timing difference between the actual and optimal timing (zero cross line or minimum error value).

From the coordinate data of the throw in Figure 3-7, the corresponding vertical error curves derived from the thumb and dart trajectories are described in Figure 3-8.

3.1.6 Time-window length for successful throwing and timing error

To evaluate the throwing quantitatively, we introduced two indexes: time-window length (TWL) and timing error (Et).

We defined the time-window length for successful release as the absolute time difference between the moment at which the vertical error curve derived from the dart entered the hit zone and the time of release (Figure 3-8). In each subject, TWL was calculated and averaged within the successful throws. Although a TWL for the successful release can be considered as the length of an ideal time range where all single release moments could result in a successful throw, the current definition results in an under-estimation of the ideal TWL since we did not include the period after the time of release.

We measured timing error (Et) based on a previous study [16], by taking the absolute of the timing difference between the actual and optimal release moments. The latter is determined by the moment that the blue curve crossed the zero line (Figure 3-8). In some throws, if the error curve did not cross the zero line, the optimal release would be determined by the moment when the curve got the smallest value within 10 ms after the time of release. The data of the curve later than 11 ms after the release moment were eliminated since the dart at that time flew far away in that period.

In some unsuccessful throws, the error curve did not cross the hit zone, resulting in non-existent TWL. Moreover, the averaged TWL was used to clarify the motor strategies of skilled throwers [16-17] through the relationship with other averaged kinematic parameters. Therefore, unsuccessful throws would skew the average value of TWL. Thus only data of successful throws were analyzed.

Also, the variability of release times (VRT) was calculated by the standard deviation of release moments relative to the zenith of the hand path to investigate whether stabilizing the release times was used to compensate for high timing sensitivity, as reported in a previous study [17].

3.1.7 Correlation between hand trajectory and the strategies

To test the first hypothesis (see "Hypothesis", section 2.2.5), which investigates the relationship between the hand trajectory and throwing strategies, first, we calculated the average of the peak values (spatially) and peak times relative to the release moment (temporally) of the error curves derived from the thumb (the red curve in Figure 3-8). Next, the relationship was investigated by the correlations between these two parameters and TWL. Moreover, we also examined the relationships between the standard deviations of two parameters (peak values and peak times) and TWL to test whether stability in the hand trajectory reflexes the strategies.

3.1.8 Correlation between kinematic parameters and the strategies

Skilled throwers have to control complex combinations between the proximal joints (elbow and wrist) and hand trajectory and release the dart at an appropriate speed and direction. Consequently, the strategies of experts related to timing sensitivity might be caused not only by the hand trajectory as suggested by previous studies [16-17] but by other kinematic parameters of proximal joints and the dart. That is, angular velocity, acceleration, and jerk of the elbow and wrist joints, and speed and direction of the dart at the release moment. Therefore, correlations between these parameters and TWL were investigated in this study.

3.2 Results

3.2.1 Influences of wearing devices and markers

The vertical error was not significantly different between the *baseline* and *post* sessions ($p >$ 0.05, all, Table 1), which means experts have quickly adapted to the discomfort caused by attaching the electrodes and markers during the *post* session. Importantly, there was no effect of the discomfort on the following *throwing* stage, which was the main experiment. There was a possibility that by learning, the experts compensated for their performance degradation during the *post* session. However, the possibility was very low, because the number of throws is only 18, and it is natural to consider that the effect of attaching electrodes on the motor skill of experts is quite limited.

3.2.2 Performance on the board

Table 1 shows the successful throwing rate and the mean of the absolute vertical error ($|y_{dart} - y_{TG}|$, see Figure 3-5) for all subjects. The former ranged from 52.38% to 69.05% (from 22 to 29 successful throws, respectively), and the latter ranged from 12.75 ± 10.43 mm. Subjects 5 and 7 exhibited the smallest success rate (52.38%) and the largest vertical error (mean value > 16 mm). If the successful rate were the criteria for accuracy (precision), subjects 4 and 6 would have been the best performers. However, if taken into account both precision and accuracy; we consider subjects 2 and 4 performed the best in the experiment since they have both high successful rate and small error on the dartboard.

Table 1. Performance of each subject.

Subject	p value	Success rate (%)	Mean of absolute vertical error (mm)	SD of vertical error (mm)
1	0.85	57.14	13.12	10.17
2	0.28	64.29	12.75	10.43
3	0.15	54.76	15.36	9.54
4	0.80	69.05	13.20	11.02
5	0.92	52.38	16.83	14.41
6	0.87	69.05	14.25	11.13
7	0.52	52.38	18.17	15.63
8	0.51	57.14	15.48	11.58

SD: standard deviation

3.2.3 Validation of the prediction model and time series of the vertical error curve

For validation of the prediction model, we examined the three indices mentioned above (see "Time series of vertical error based on dart tip movement", section 3.1.5). In this study, all the absolute estimated errors were not larger than 40.0 mm, with an average of 14.89 ± 5.0 mm among the subjects. Furthermore, a high correlation was found between the calculated and actual positions on the board (r = 0.86 ± 0.05 among subjects). Moreover, Figure 3-9A shows the correlation between the standard deviations of the actual error and calculated error (r = 0.65, p = 0.08). From the results of the three indices, the model can reasonably estimate the measurement. Furthermore, there was a significant difference between the estimated errors calculated from dart trajectories (3.30 ± 15.67mm) compared to the ones calculated from finger trajectories (-395.66 ± 109.38 mm); Z = 36, $p < 0.01$ (Figure 3-9B). The result suggested that the final resultant position of the dart estimated based on its trajectories could be more precise than that estimated from the finger trajectories as in a previous study [3].

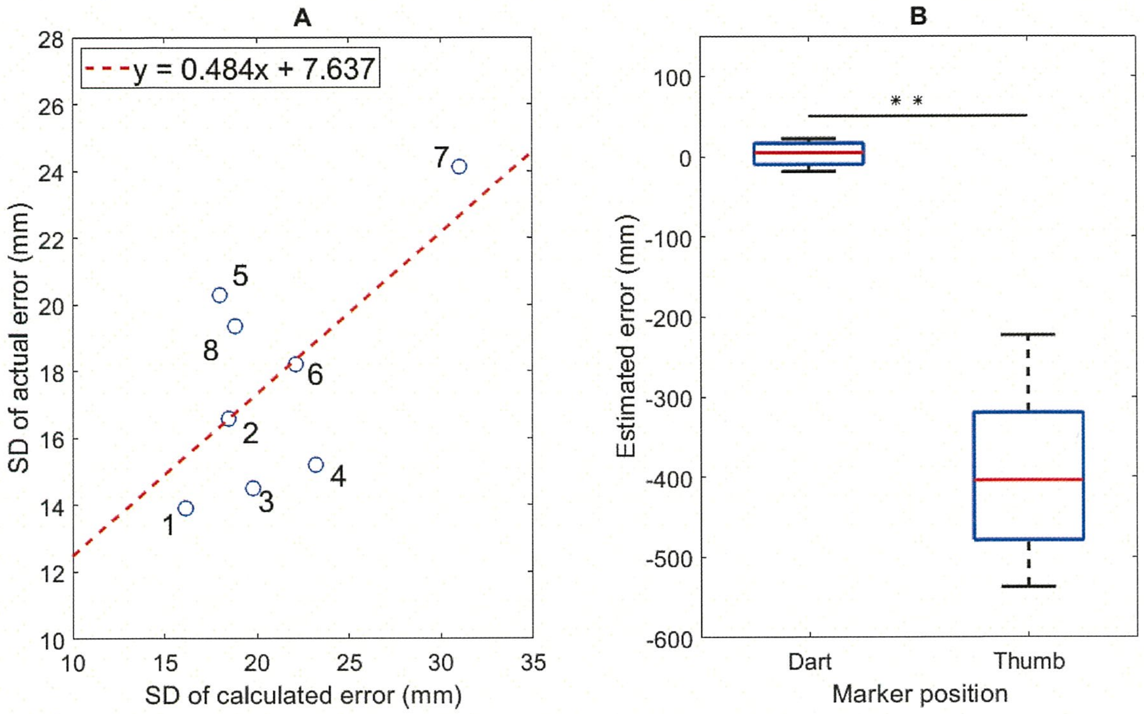

Figure 3-9. Validation of the prediction model in this study. (A) Standard deviations (SD) of the actual error and calculated error. The dashed red line represents the linear regression line. (B) Estimated errors calculated from the dart and finger trajectories. **: $p < 0.01$.

Figure 3-10 illustrates the patterns of vertical error curves derived from hand and dart trajectories (markers M1 and M2, respectively) for successful throws. The curves derived from the dart's movements crossed the hit zone only once because the values at the time of release were equal to the vertical errors measured on the board by the motion capture system.

The benefit of this method is that the error curve derived from dart movement crossed the successful zone only once before the time of release, which could be more explicit and intuitive to evaluate the TWL of a throw (Figure 3-10). Moreover, the point of optimal release was reduced to one instead of two, as compared to the previous models.

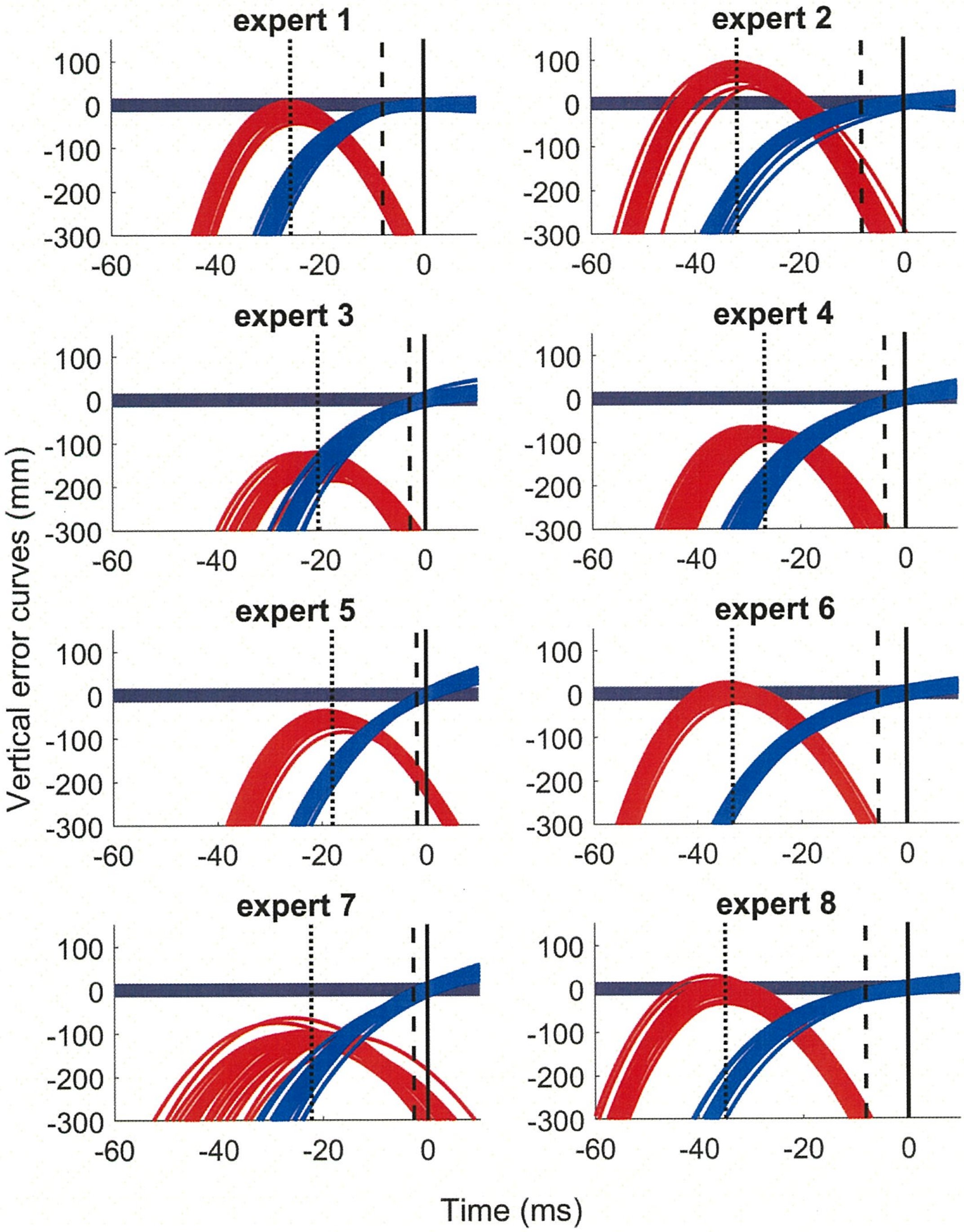

Figure 3-10. Time series of vertical error curves for all experts. Red lines represent the vertical error curves derived from hand trajectory. Blue lines indicate the vertical error curves derived from dart trajectory. Black lines demonstrate the time of release. Dotted black lines indicate the average timing at the peak value of red curves relative to the time of release. Dashed back lines represent the average TWL relative to time of release. The hit zone is displayed in dark gray.

3.2.4 Two strategies of skilled dart throwers

To comprehensively elucidate the identified strategies of the experts, we analyze the relationship between several kinematics parameters. Figure 3-11 shows the results; only the high correlations with $p < 0.05$ were shown in the graph. The average of each variable in successful throws (from 22 to 29 throws, see Table 1) is shown in Table 2. Although there are several statistically high correlations were confirmed, we focused on kinematic parameters that had high correlation with the TWL since timing sensitivity could be considered as one of the factors that constitute motor strategies of skilled throwers [16-17].

As can be seen in Figure 3-11, the TWL was statistically correlated with the peak value and peak time (relative to the time of release) of the error curve derived from the thumb, the timing error (Et), the dart speed and angular acceleration of the wrist at the time of release.

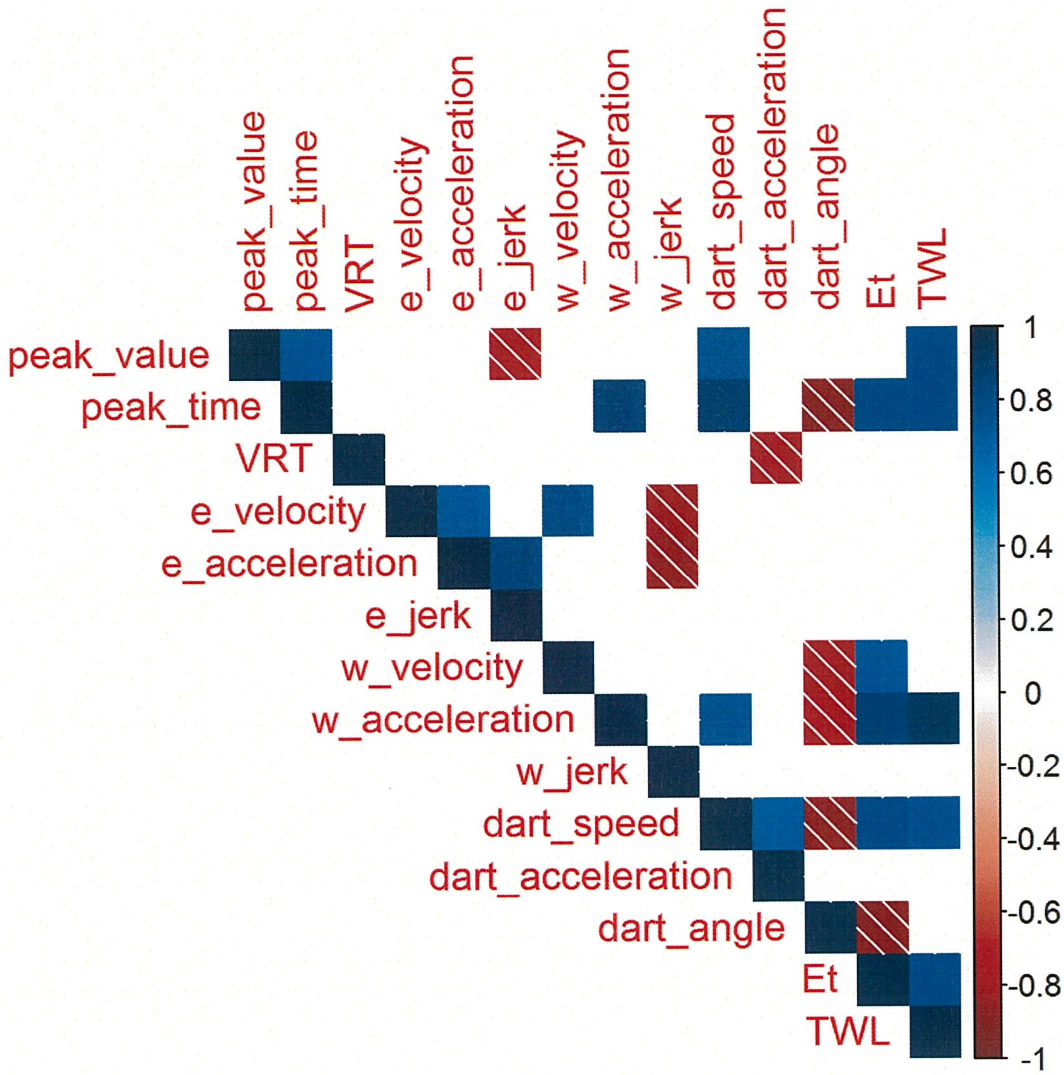

Figure 3-11. Correlations between kinematic parameters. The meaning of each variable is explained in Table 2. Only statistically significant correlations ($p < 0.05$) were displayed in colored squares. Blue and red squares represent positive and negative correlations, respectively.

Table 2. Meaning of each variable represented in Figure 3-11.

Variable Name	Meaning
peak_value (mm)	The peak value of the vertical error curve derived from the thumb
peak_time (ms)	The time when the error curve derived from the thumb relative to the time of release
VRT (ms)	Variability of release times relative to the zenith of the hand path
e_velocity (degree/ms)	The angular velocity of the elbow at the time of release
e_acceleration ($degree/ms^2$)	The angular acceleration of the elbow at the time of release
e_jerk ($degree/ms^3$)	The angular jerk of the elbow at the time of release
w_ velocity (degree/ms)	The angular velocity of the wrist at the time of release
w_ acceleration ($degree/ms^2$)	The angular acceleration of the wrist at the time of release
w_jerk ($degree/ms^3$)	The angular jerk of the wrist at the time of release
dart_speed (m/s)	The speed of dart at the time of release
dart_acceleration (m/s^2)	The acceleration of dart at the time of release
dart_angle (degree)	The angle of dart at the time of release
Et (ms)	Timing error
TWL (ms)	Time-window length for successful release

Figure 3-12A shows the relationship between TWL and Et across the experts, with a high correlation (r = 0.81, p = 0.02). TWLs of subjects 1, 2, and 8 were relatively high, around 8.08 ms, whereas TWLs of experts 3, 4, 5, and 7 were shorter, from 1.77 ms to 3.90 ms. In this study, the Et of the experts ranged from 1.45 to 4.44 ms.

Figure 3-12B shows the correlation between Et and the variability of release times (VRT) relative to the zenith of the hand, which is quite low (r = -0.52, p = 0.19). Seven of eight experts performed the task similarly with very small VRT (ranged from 0.78 ms to 1.65 ms), except expert 7 (3.38 ms).

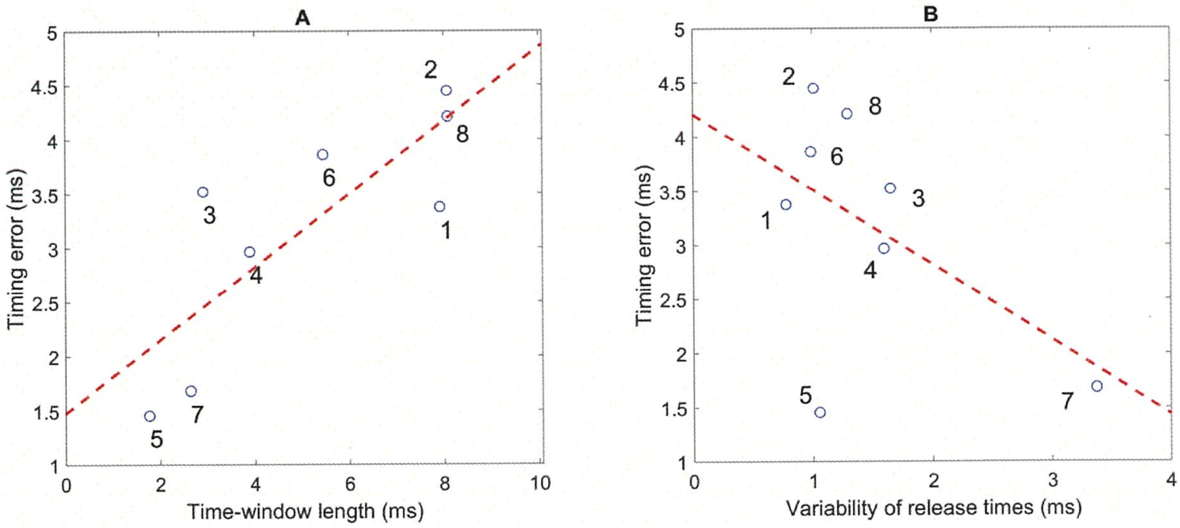

Figure 3-12. Relationships between timing parameters reflecting strategies of the experts. Relationship between time-window length (TWL) and timing error (Et), and relationship between Et and the variability of release times relative to the zenith of the hand path. In both figures, the dashed red line represents the linear regression line.

With regard to the time series error curves derived from thumb movement, most of the curves in experts with longer TWL crossed or peaked very close to the hit zone. Meanwhile, the peaks of the curves of high timing sensitivity (shorter TWL) did not reach the zone, with large error values before the time of release. In terms of timing, there was a difference in the peak times relative to the time of release, with about 32 ms in experts with longer TWL (e.g. experts 2 and 8) and 20 ms in experts with shorter TWL.

3.2.5 Relationship between the hand trajectory and the two strategies

To clarify whether kinematic parameters of the hand trajectory were correlated with the strategies, we evaluated the correlations between the average of peak values and peak times relative to the time of release Figure 2-1of the curves derived from the thumb and TWL. We found a significantly strong correlation between the means of the two parameters of the error curves from the thumb and TWL, with $r = 0.79$, $p = 0.02$ at peak value (Figure 3-13A) and $r = 0.80$, $p = 0.02$ at peak time (Figure 3-13B). This result suggests that the strategies of experts characterized by the TWL were correlated with kinematic parameters of the hand trajectory in both spatial and temporal domains.

However, we did not find a strong correlation between the standard deviations of the two parameters and TWL, with $r = 0.09$ at peak value and $r = -0.44$ at peak time.

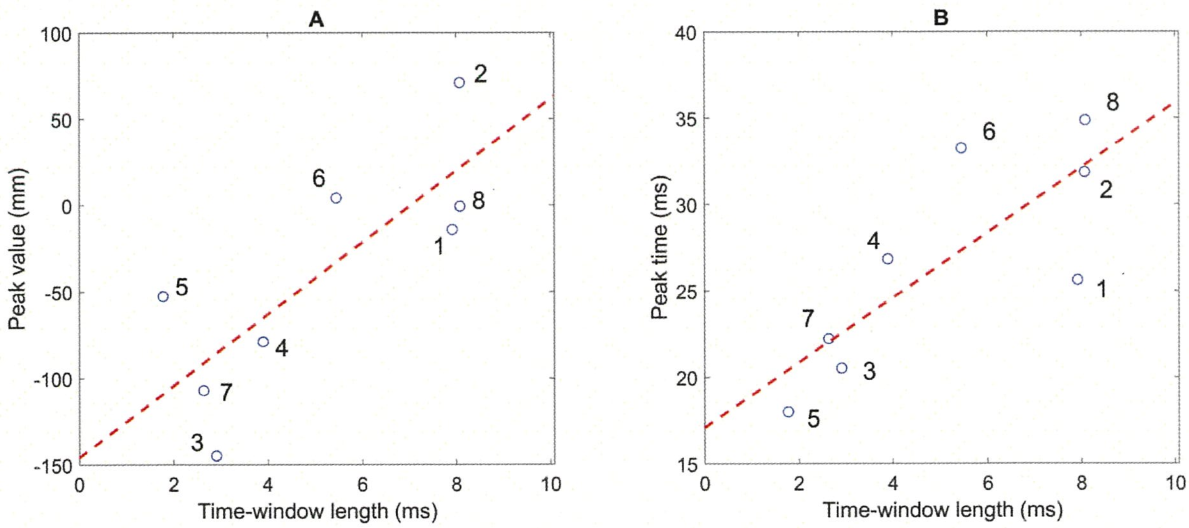

Figure 3-13. Relationship between hand trajectory and the strategies. (A) Relationship between hand peak values of error curves derived from hand trajectory and TWL. Relationship between peak times relative to the time of release of error curves derived from hand trajectory and TWL. In both figures, the dashed red line represents the linear regression line.

3.2.6 Kinematic parameters of the dart and human effects on the two strategies

As shown in Figure 3-14, we found strong correlations between the dart's speed at the time of release and the TWL across all experts ($r = 0.78$, $p = 0.02$), suggesting that throwing at a high speed leads to a longer time-window for a successful release. Similarly, we found that wrist angular acceleration was highly correlated with TWL ($r = 0.93$, $p = 0.0009$, Figure 3-15). However, we did not find any correlations in kinematic parameters at the elbow joint.

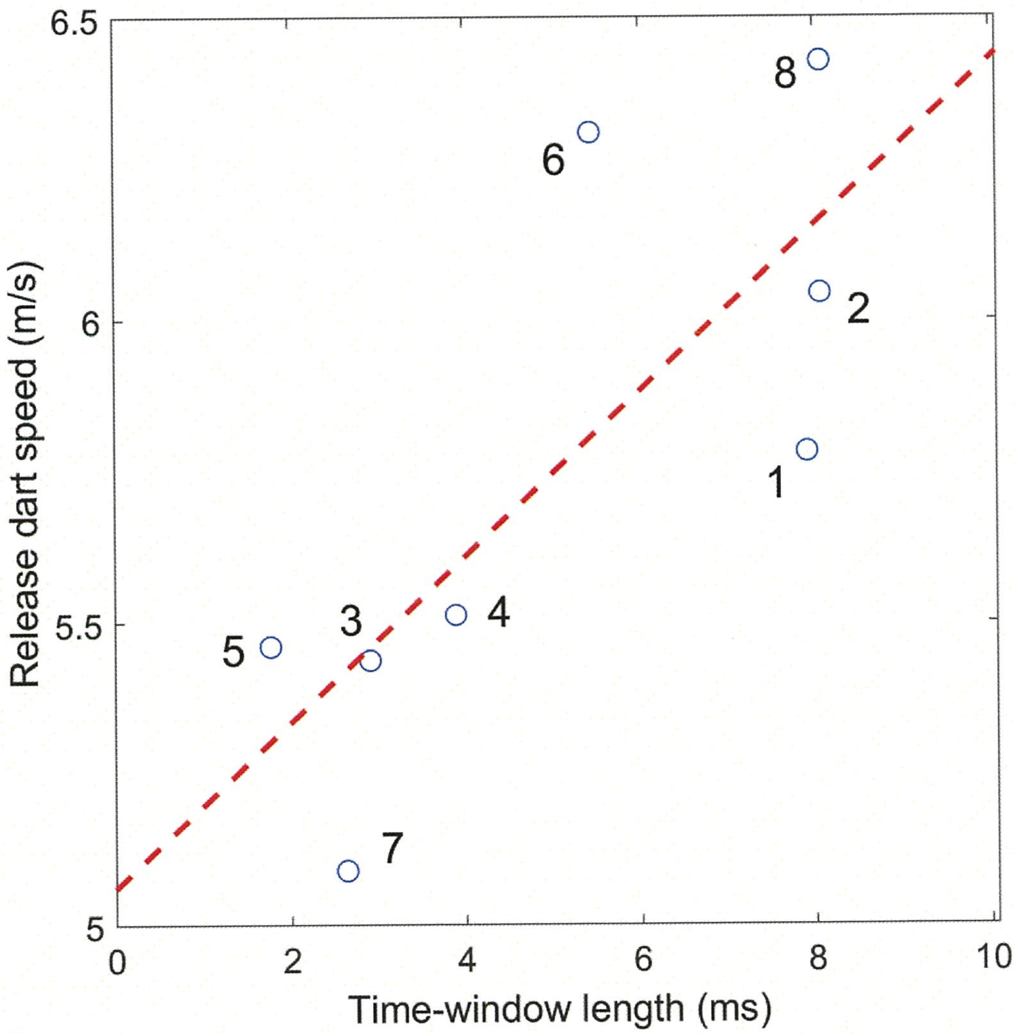

Figure 3-14. Relationship between the speed of dart at the time of release and TWL. The

dashed red line represents the linear regression line.

We also found that the larger release speed was associated with a smaller release angle of the dart to obtain the accuracy (r = -0.86, p = 0.006, see Figure 3-16) across all subjects, which reflects patterns of the arc after the time of release of the two strategies, i.e. high and low arc.

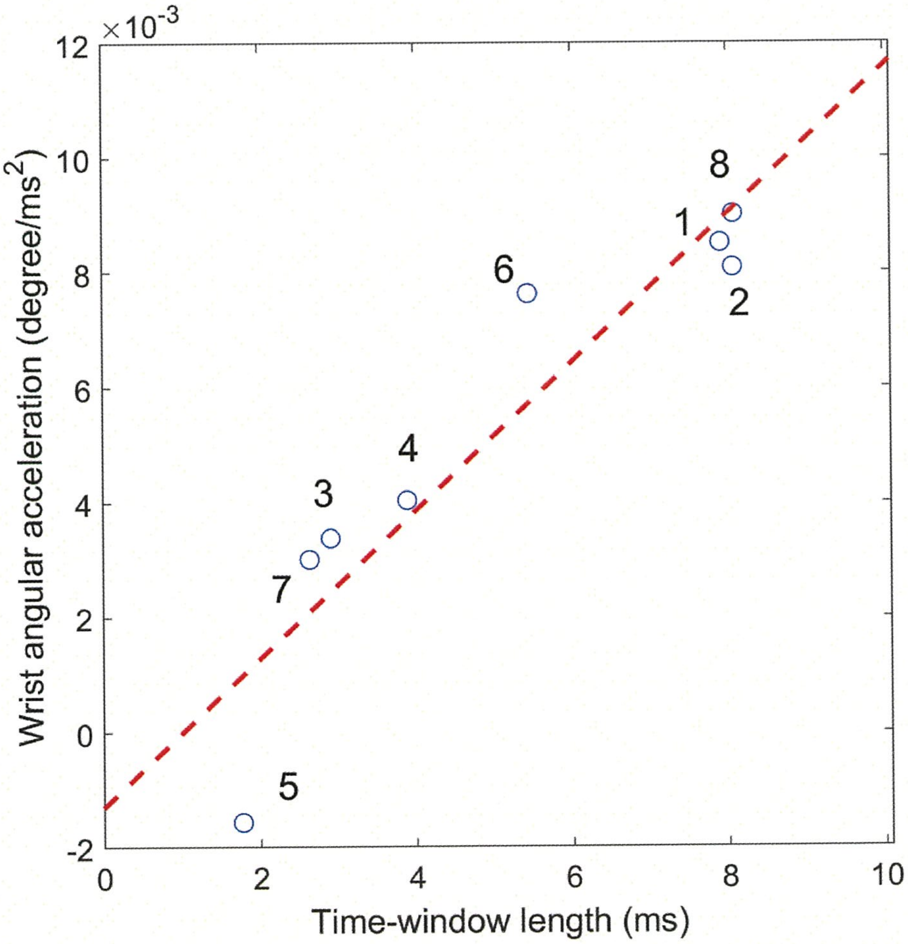

Figure 3-15. Relationship between wrist angular acceleration at the time of release and TWL. The dashed red line represents the linear regression line.

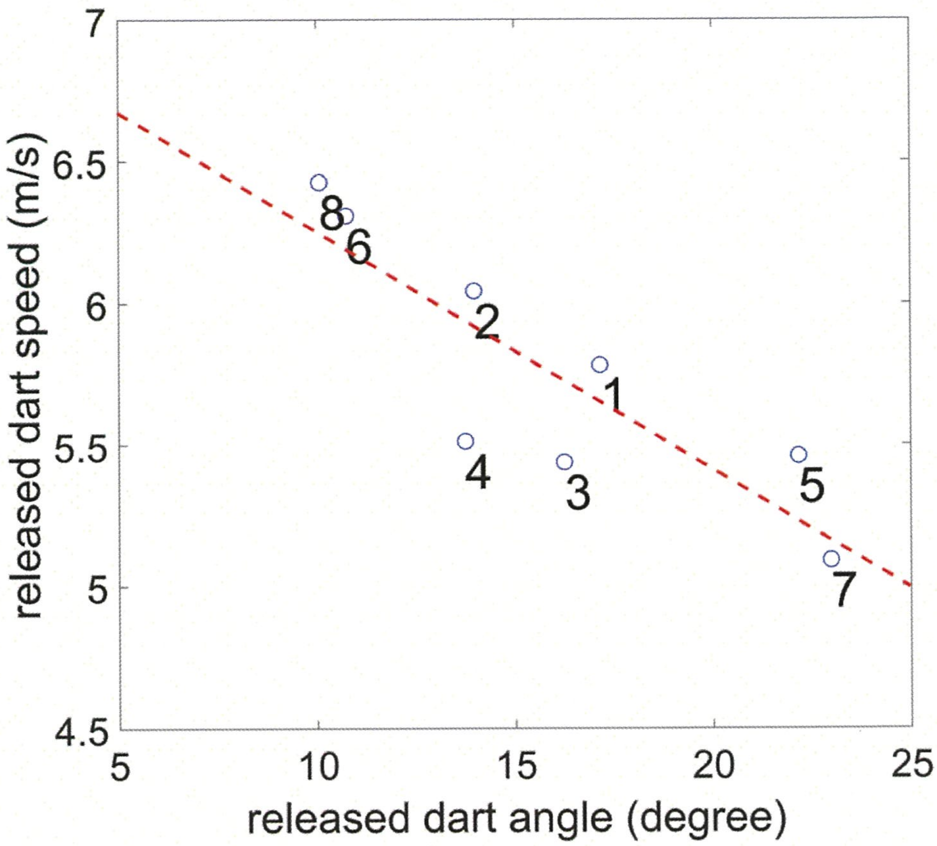

Figure 3-16. Relationship between release speed and angle of the dart at the time of release. The dashed red line represents the linear regression line.

3.3 Discussion

3.3.1 Confirming the two strategies

The mean value of Et and the correlation trend were similar to a previous study in dart throwing [17]. In addition, longer TWL was associated with larger Et (r = 0.81, Figure 3-12A) among all subjects, which confirms that there were two strategies in experts: reducing timing sensitivity (long TWL) and reducing timing error.

In the current study, the correlation between Et and VRT was low (r = -0.52, Figure 3-12B), which means that stability in the release times was not used to compensate for high timing sensitivity. We did not reduplicate the high correlation (r = 0.93) as in a study [17] because of the following reasons. First, experts 1, 2, and 6 (with longer TWL) performed the task with the smallest VRTs, which means that very skilled throwers with low timing sensitivity could also stably control the release relative to the zenith of the hand path. Second, using the zenith of the hand as a reference to evaluate VRT might be imprecise since the kinematic landmark is also variable in the hand trajectory [3]. In other words, a lower variability of release times is not likely utilized to compensate for a shorter TWL as reported in [17].

3.3.2 Spatiotemporal relationship between hand and dart trajectory

To clarify whether experts might utilize the optimized hand trajectory in the acceleration phase to reduce timing sensitivity, we examined the relationship between kinematic parameters of the hand trajectory and the TWL.

We found high correlations between the peak values (r = 0.79) and peak times (r = 0.80) of the error curve derived from the thumb movement and the TWL (Figure 3-13). The experts with the reducing timing sensitivity strategy might pre-plan the move hand trajectory so that the corresponding error curve derived from the thumb crosses the hit zone about 30 ms relative to the time of release (see red curves in Figure 3-10). Afterward, the throwers kept the direction of dart suitably (e.g., low-release direction) and drove the proximal joints forward at a particular speed for a successful throw. It could be considered a skill in spatial control with less focus on timing precision. This result aligns with that of a previous study [16], which reported that the key of this strategy is that the hand trajectory can be planned beforehand and does not rely on the feedback of the previous throws. With regard to throwing tasks, previous studies discussed "modifying the hand trajectory" to increase the TWL as a strategy [17] or a training effect [16], but the particular pattern of this modification or improvement was unclear. In this approach, the author has clarified the point, but has analyzed the interaction between the hand and projectile trajectory.

In contrast, the hand trajectory of the throwers perform with shorter TWL was not optimized or all error curves did not cross the hit zone. Moreover, the peak was closer to the time of release, which caused them to choose the time of release more strictly (Figure 3-10). One could hypothesize that the hand trajectory of these experts was less variable to achieve accuracy within a shorter time-window. However, the correlations between the variability of kinematic parameters of the hand trajectory and TWL were not high: $r = 0.09$ (peak value) and $r = -0.44$ (peak time relative to the time of release). Especially, expert 7 had large variability in both peak value and peak time, but the subject had a very narrow time-window. This result indicates that the variability of the hand trajectory might not be representative of the throwing strategies, or experts with shorter TWL did not necessarily have hand trajectories that were more stable and stereotyped than the experts with longer TWL. Instead, their strategy might be based on their practice of timing precision or other stable kinematic parameters.

3.3.3 Relationship between kinematic parameters at the time of release and TWL

Dart throwing is a sophisticated skill requiring several combinations of skills, such as forearm extension, wrist flexion, and release the projectile with appreciable speed, and direction to hit a very small target. In this experiment, the target's diameter is just 32 mm. As a result, tiny displacements and variability in various parameters during throwing such as vertical lift of the shoulder, elbow, or dart at the time of release can significantly influence the performance, even though experts could compensate for the variability [14,15]. Thus, kinematics of the proximal joints (elbow and wrist) hardly influence the performance directly of an expert during a throwing task. However, if considering average values, we could analyze which parameters contribute to the different strategies among different experts.

We found that the TWL of experts increased as the angular acceleration of the wrist and dart's speed at the time of release increased across all eight subjects, with strong correlations $r = 0.93$, $p = 0.0009$ (Figure 3-14), and $r = 0.78$, $p = 0.02$ (Figure 3-15) ,Figure 3-14 respectively. The first hypothesis was supported by strong correlations. If an expert released a dart with a high speed, the thrower could release sooner or later since the dart low arc (flew straighter), and was less affected by gravity. With such a high speed and a wrist angular acceleration during elbow extension, these experts might have to adjust the hand trajectory appropriately soon, about 30 ms before the time of release (Figure 3-10). Without this manner, it was too difficult for the thrower to release at the "extremely accurate" moment with such fast dart speed and angular wrist angular acceleration.

Conversely, in experts performed with high timing sensitivity (shorter TWL), the throwers released a dart with a lower speed, resulting in a high throwing arc to compensate, as the projectile was strongly affected by the gravity. Thus, with high timing sensitivity, these experts might accelerate the wrist joint slower for easier release at an appropriate moment and do not need to realize the optimized hand trajectory. The results also imply that in dart throwing, the wrist joint, which directly grips and transfers the speed to dart, might have a more significant contribution in the skills of experts, rather than the farther proximal joint (elbow).

One could hypothesize that taller dart players chose the low arc (high-released speed) since the release vertical location of the dart was closer to the height of the bull's-eye. However, in the cases of experts 2, 3, 4, 6, and 8, heights were similar (from 182 to 187 cm), but their strategies were different; additionally, this was also similar for experts 1 and 7 (170 cm in height). This implies that the strategy of low or high arc (long or short TWL) depends on the preference of players.

3.3.4 The two strategies in a training perspective

In training, reducing timing sensitivity with spatial control would be easier for beginners. It is too difficult for inexperienced throwers to realize and throw with a TWL between 1.77 ms to 3.9 ms, like the experts in this study. Further, it is also difficult for them to have the ability to compensate for the variability within such a low time-window. Instead, by separating the two error curves derived from the hand and dart, the novices can first practice improving the wrist's strength to accelerate faster and optimize the hand path based on the feedback of the derived error curves as experts with longer TWL, regardless of the error on the dartboard. After getting a good hand trajectory, the beginners will practice control and release the dart with appropriate speed and direction.

3.4 Conclusion

In this chapter, throughout kinematics parameters the two strategies of experts in dart throwing were confirmed, namely, (1) reducing the timing sensitivity and (2) reducing timing error. By separately capturing both the kinematics of the projectile and the hand trajectory and analyzing these parameters, the methodology used was more precise and intuitive. In fact, the prediction model to estimate the final position by the dart trajectory until the moment of impact was confirmed to be more precise than a previous model. Furthermore, the optimized time of release was only one, instead of two as previous models, which enables us to determine and evaluate the TWL and Et more intuitive. We indicated that the two strategies reflected the skill of spatial or timing control along the hand trajectory before the time of release, by the peak value and time of the derived error curve relative to the time of release.

In addition, the dart speed and wrist angular acceleration at the time of release were the two kinematic parameters that determined the throwing strategy of experts; in other words, it was not simply the variability of the hand's path, as reported in previous studies.

Chapter 4. Analysis on EMGs in dart throwing

4.1 Co-activation analysis

This part mainly investigates EMG patterns during dart throwing of novices and intermediate level players [99-100] to clarify the difference of muscle intensity patterns between different skill levels. Namely, the muscle co-activation at the elbow joint produces force during the acceleration phase. This negative factor is investigated and compared between *beginner*, *intermediate*, and *expert* groups. The EMG recording in the expert group has been described in Chapter 3 (see "Experiment", section 3.1.1).

4.1.1 Methodology

a) Co-activation in novices and intermediate dart players

Subjects

Six males and one female took part in the experiments, with their ages ranging from 23 to 27 years old. Three of the subjects (two males and one female) who had played and practiced dart from three to four years, were considered as intermediate level (subjects E, F, and G). Four subjects with less experienced in dart (i.e., subjects A, B, C, and D, but B had more experience), were considered as beginners.

Experiment

The experiments with regard to four beginners were implemented separately in kinematics and EMG sections [100]. In the EMG recording section, 3 muscles related to the nature measuring EMG variables during dart throwing behaviors were examined, i.e. *dorsal* *interossei* (*DI I*) – finger muscles for the release movement, *Biceps brachii (BB) and Triceps brachii (TB)* – flexor and extensor muscles of the elbow for the forearm driving movement.

In this experiment with regard to the intermediate group [99], the three muscles mentioned above in the beginner group, and a further finger muscle were investigated: *dorsal interossei II* (*DI II*). Moreover, kinematic data were also recorded simultaneously by the two high-speed cameras, 240 Hz and 210 Hz, and the latter was used to detect the time of release. Movements of the elbow joint were captured by markers attached on the shoulder, elbow, and wrist.

Procedure

Before the experiments, participants in both groups were asked to practice 20 throws to get accustomed to darts, standing position (237 cm apart from the board) as well as the target (bull's-eye on the dartboard, 172 cm in height). Next, the skin of subjects was shaved and cleaned with paper and alcohol to reduce the resistance. Four EMG electrodes (Nihon-Kohden, Japan) were attached on *TB, BB, DI* I and *DI II* muscles on the throwing arms. Afterward, each subject asked to perform 45 throws, which were used for data analysis.

Data Processing

The recorded muscle activation patterns were sampled at 1000 Hz and converted into moving average root-mean-square (RMS) signals with a window size (n = 30 samples, chosen by trial and error, resulting in a smooth signal, see Equation 3) afterward.

$$V_{RMS}(t) = \sqrt{\sum_{n=1}^{30} |V(t-n)|^2} \quad (3)$$

Where V_{RMS} (t) is the amplitude of RMS signal at time t, V is the amplitude of the recorded EMG signal (raw), n is the window size.

All the data of muscle activities were processed in Matlab (2007b). The contraction duration of each muscle was determined from the first moments that the RMS signal of *TB*, the primary muscle activated to drive the forearm forward, reached 10% of the peak (defined as *start point*) [102]. We aligned and took an average of all 45 throws from the *start point*. Afterward, the co-activation level of the antagonist muscle (*BB*) in each subject was quantitatively evaluated by the integral of 200-ms RMS signal (iRMS, see Equation 4) after the *start point*.

$$\mathrm{iRMS} = \int_{ST}^{ST+200} V_{RMS}(t)dt \quad (3)$$

Where iRMS is the integral of the co-activation in the antagonist muscle (*BB*), ST is the *start point*, $V_{RMS}(t)$ is the amplitude of RMS signal at time t.

4.1.2 Results

a) Performance on the dartboard

To investigate the relationship between skill levels and co-activation levels, first, the performances of three beginners, four intermediate, and eight experts (in Chapter 3) was illustrated in Figure 4-1. It can be seen that the vertical error of the intermediate level players (subjects E, F, and G) was better than beginners, but were not small as compared to the experts performed.

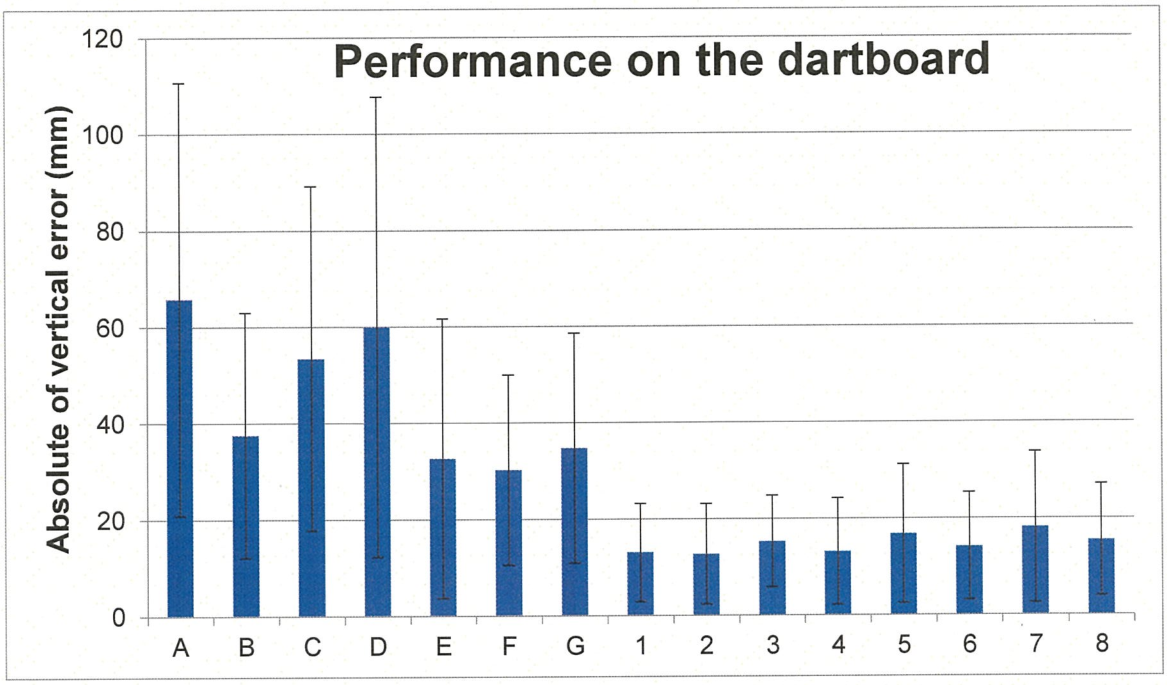

Figure 4-1. Performance on the dart board of all subjects in the previous experiments of dart throwing, beginners (A-D), intermediate (E-G), and experts (1-8).

b) Co-activation phenomenon in the intermediate and beginners group

Figure 4-2 illustrates the RMS of EMG signals in four beginners. It can be seen that the antagonist (*BB*) activated in all subjects in the beginner group, except subject B, the best performer in the experiment among the beginner group.

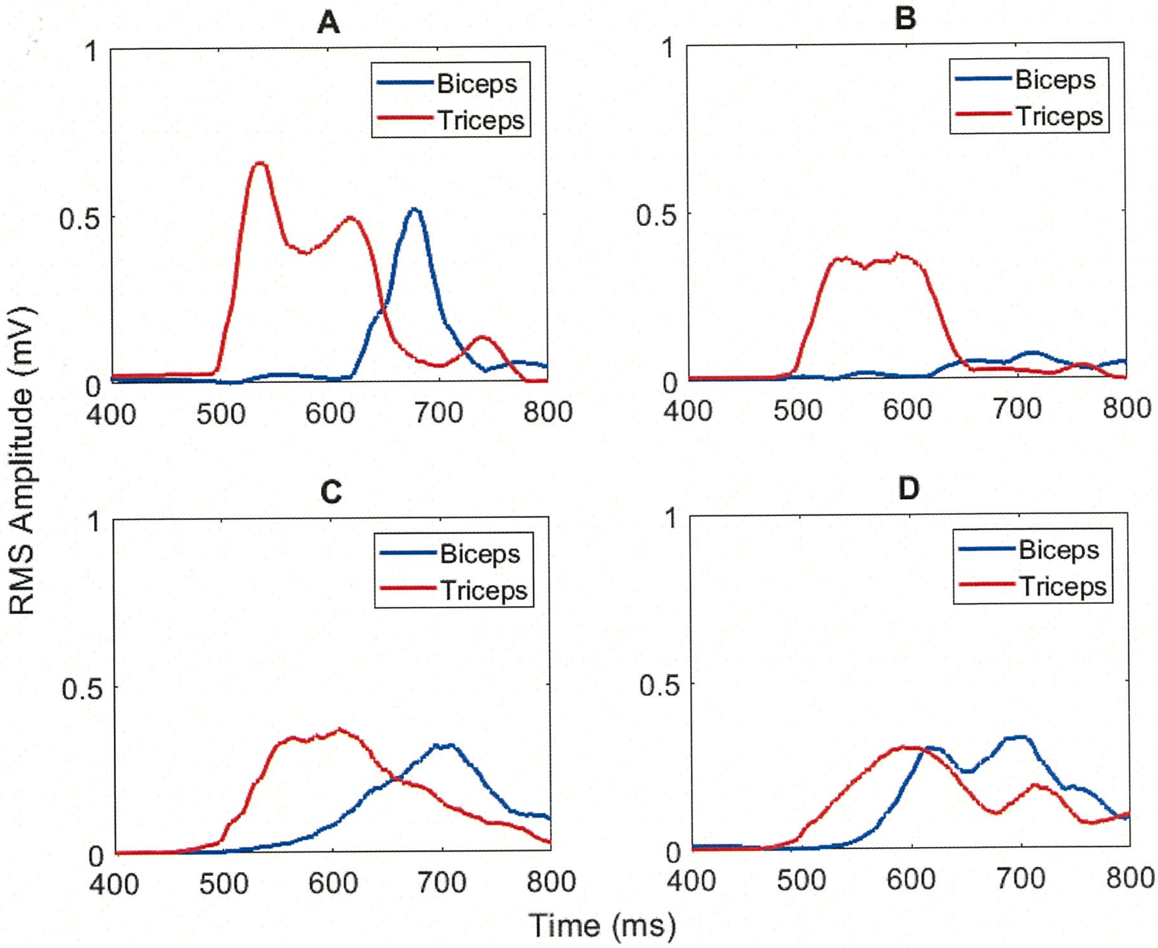

Figure 4-2. EMG signals recorded in the *beginner* group. The first time in which the RMS signal reaches 10% of the peak value at t = 500.

Figure 4-3 shows the RMS signals of three subjects at the intermediate level. It can be seen that the antagonist (*BB*) almost relaxed during the movement, suggesting that players with the intermediate level performed the task with the more economical manner in controlling muscle activation, which was similar to the *expert* group (see "Results", section 4.1.2d).

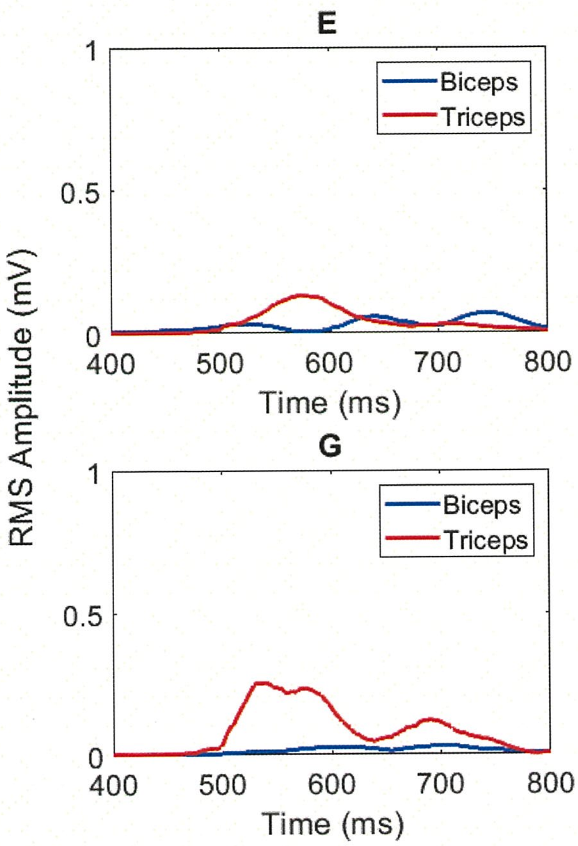

Figure 4-3. EMG signals recorded in the *intermediate* group. The first time in which the RMS signal reaches 10% of the peak value at t = 500.

c) Correlation between co-activation level and performance

There was a high statistically correlation between performance on the dartboard (standard deviation) and the antagonist activation level of *BB* in all subjects ($r = 0.72$, $p = 0.0024$, Figure 4-4). The result implies that co-activation might lead to worse performance in the beginners, except subject B.

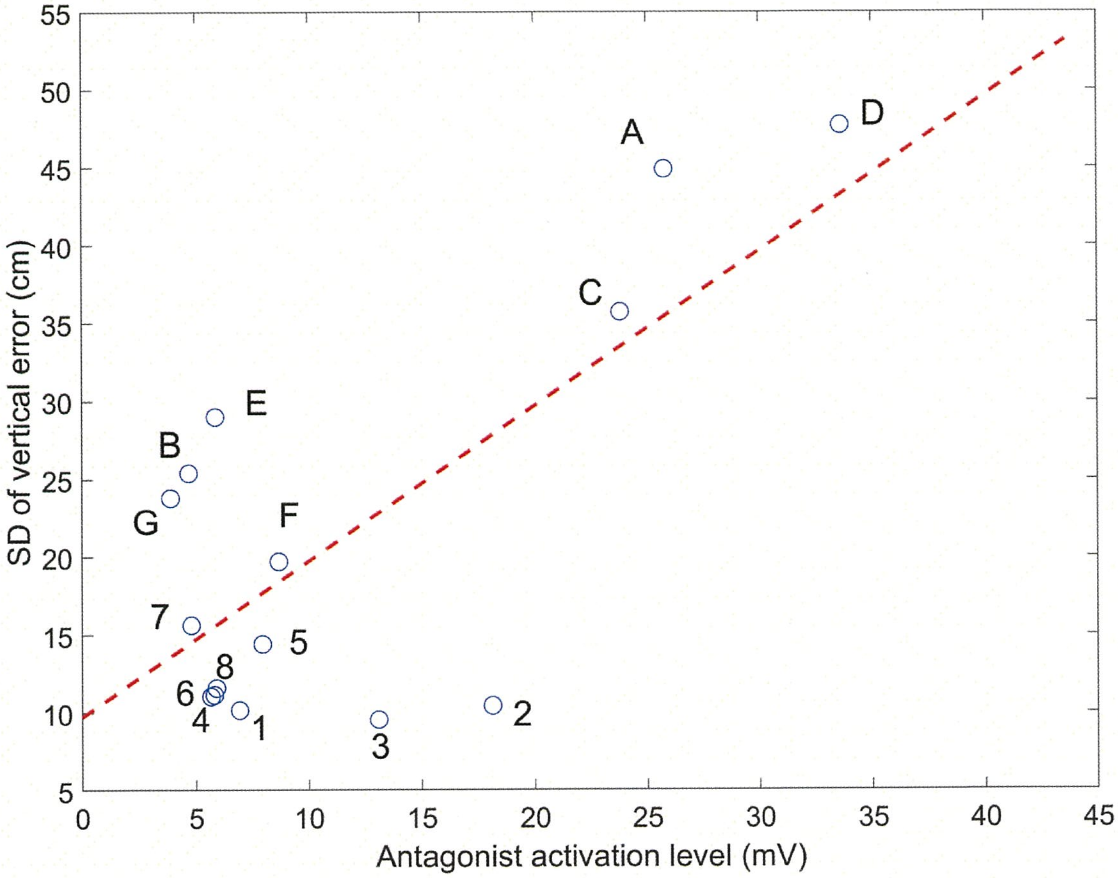

Figure 4-4. Correlation between antagonist activation level and performance of the beginners (A-D), intermediate players (E-G), and experts (1-8). The dashed red line represents the linear regression line. SD: standard deviation.

4.1.3 Discussion

It is suggested that after a period of training, learners could obtain the more effective coordination of muscle activities by removing futile muscle activities, or reduce level the co-activation at the antagonist muscle [20]. The results of the intermediate group (subject E, F, and G) and the skilled experts (in Chapter 3) proved the hypothesis, with the decreased contraction intensity of *BB* during the acceleration phase. These findings are also in accordance with [103], where the contraction intensity of *TB* (antagonist muscle) was decreased after a training period of seven weeks with concentric contractions. Similarly, after an isometric resistance training [104], the antagonist muscles of the knee extension (*hamstring*) in the trained leg were reduced 20% after the first week of training, associated with an increase of 32.8% the extensor maximal voluntary contractions. Moreover, a high antagonist level might be an indicator of novices in dart throwing since this parameter was highly correlated with the vertical error ($r = 0.72$, $p = 0.0024$).

Previous researchers have confirmed that athletes showed significant lower antagonist activation in leg muscles than sedentary subjects [84], perhaps due to typical activities of muscles involved in their discipline [40]. Amiridis et al. indicated that the semi-tendineous muscle (antagonist muscle in knee extension) of the sedentary subjects was significantly higher than skilled jumpers [84]. The result was in agreement with the current thesis, where the relatively high activation levels of the *BB* in the *beginner* group as compared to the *expert* group during the acceleration phase of throwing. From Figure 4-4, in most experts, muscle activity of *BB* (the antagonist muscle) was relatively low before the time of release, whereas the activation level of TB (agonist muscle) was high.

In a study on sedentary subjects, Bazzucchi et al. [105] reported that the antagonist co-activation of *BB* was higher than *TB* due to the demand on encountering gravity in daily activities, which means that the unskilled dart throwers in this study might have already a high unexercised antagonist (*BB*). As a result, in a training perspective, the activation of *BB* in beginners should be reduced after an isokinetic exercise before conduct the dart throwing task. Thus, as in future works, the author proposed an EMG-based system that monitored the antagonist co-activation of the novices with the isokinetic exercise during a period. Afterward, the performance of trained and untrained subjects would be quantitatively evaluated to confirm the effectiveness of the proposed system. Additionally, further investigations of the co-activation should be carried out in skilled players of other movements in the future together to generalize the conclusion.

4.2 Muscle synergies in dart throwing

4.2.1 Methodology

a) Experiment

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. The subjects were asked to conduct 60 throws, aiming to the bull's-eye [101], after verbal commands of an experimenter.

This section focuses on muscle activity analysis. EMG signals of 10 selected muscles on the main articulations (shoulder, elbow, and wrist) along the throwing arm were recorded (see Figure 4-5) by surface electrodes. Before attaching the electrodes, the 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 (WEB-5000, Nihon-kohden, Japan) and then fed to a PC through to an A/D board. A custom-made digital circuit detected the time of release with an LED by adhering two thin pieces of metal tapes (width = 0.065 mm) on the thumb and index finger. The ON/OFF signal was connected to the A/D board to synchronize EMG and kinematic data.

The recorded muscles in the experiment were: *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).*

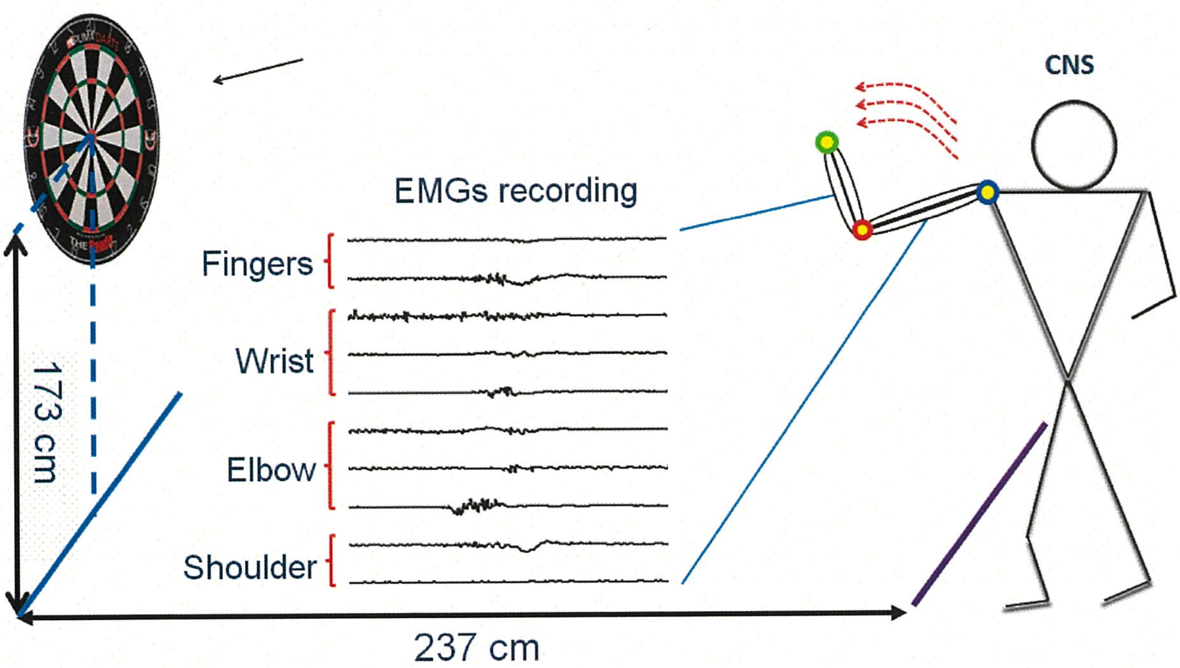

Figure 4-5. Experimental set up for EMGs recording.

b) 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 throw, we analyzed EMG signals in a throwing period (*THD*). 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 *THD* was chosen so that the time of release was in the middle. For timing normalization across trials, an envelope of EMG data of a throw 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 energetic activations between the selected muscles while throwing were. The 100-sample envelops of all total 60 throws were concatenated for muscle synergy analysis afterward.

c) Muscle synergy extraction

After data processing and time-normalization between throws (100 samples), the non-negative matrix factorization NNMF [98] was applied to the observed EMGs, with the following equation:

$$M \cong \sum_{i=1}^{N} W_i \times c_i \quad (3)$$

M was observed EMG data of all 10 muscles, which was concatenated by all 60 throws in each subject. Thus M was a 10-by-6000 matrix, representing patterns of 10 muscle activities, with 60 (throws) ×100 (samples). W represents muscle synergies that define spatial patterns whereas C represents time-series activation coefficients.

We used determination coefficient r^2 between the observed and reconstructed data to determine the number of synergies, with the criteria that the average r^2 in across subjects excess 90%. After extraction, we aligned the order of synergies of subjects by the peak of activation coefficients relative to the time of release.

4.2.2 Results

With the criteria described above, from the curve represents the relationship between the number of synergies and the determination coefficient in Figure 4-6, three muscle synergies were chosen, ($r^2 = 0.91 \pm 0.02$).

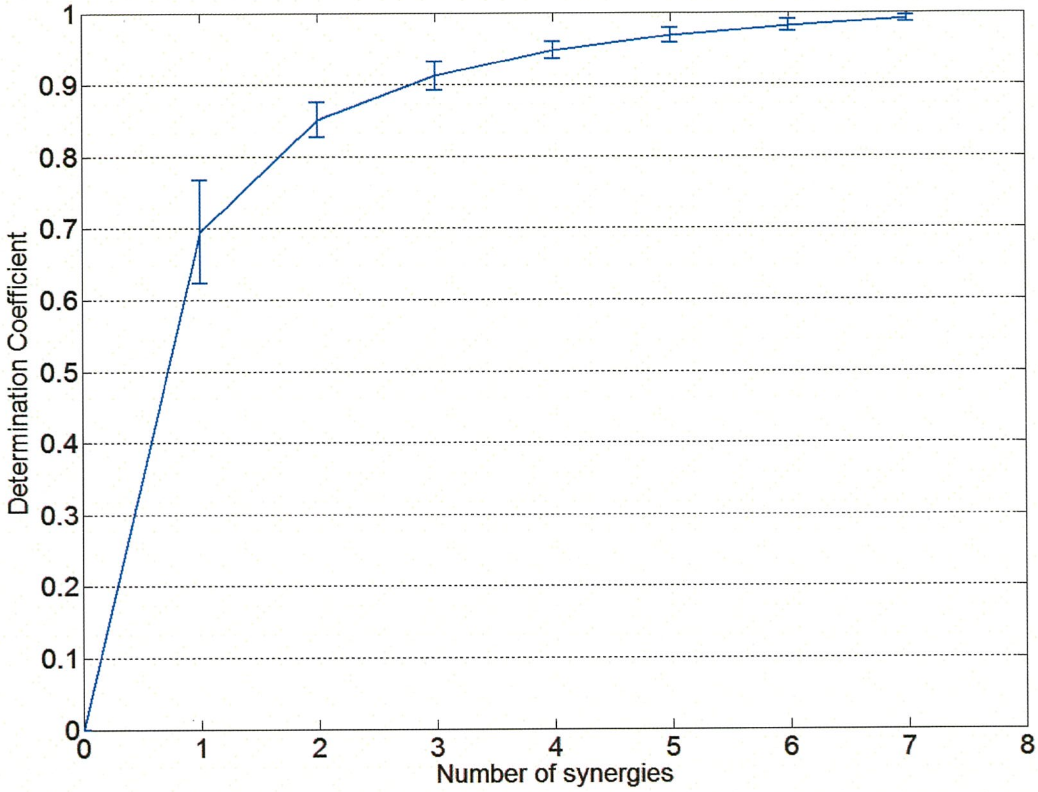

Figure 4-6. The relationship between the number of synergies and the determination coefficient after apply synergy analysis.

Figure 4-7 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.

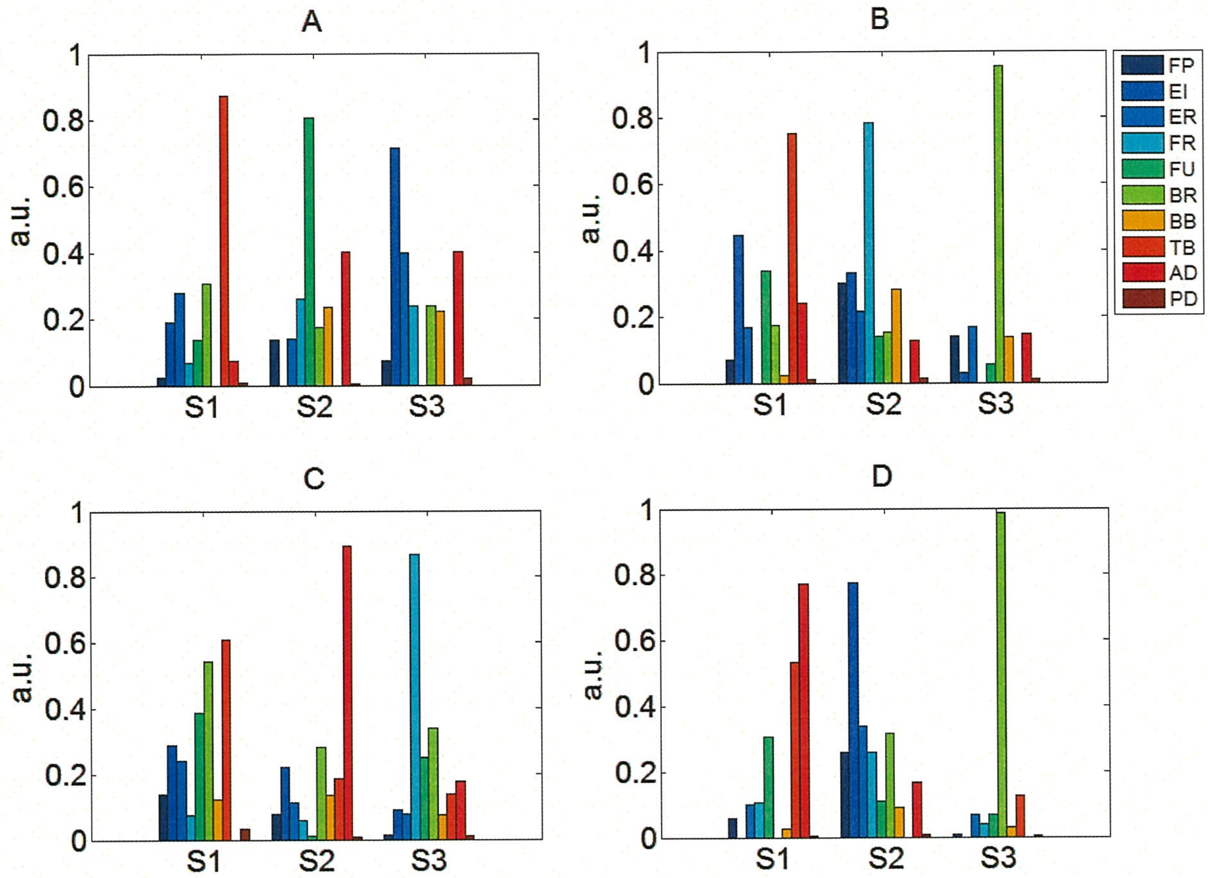

Figure 4-7. Muscle synergies of all participants.

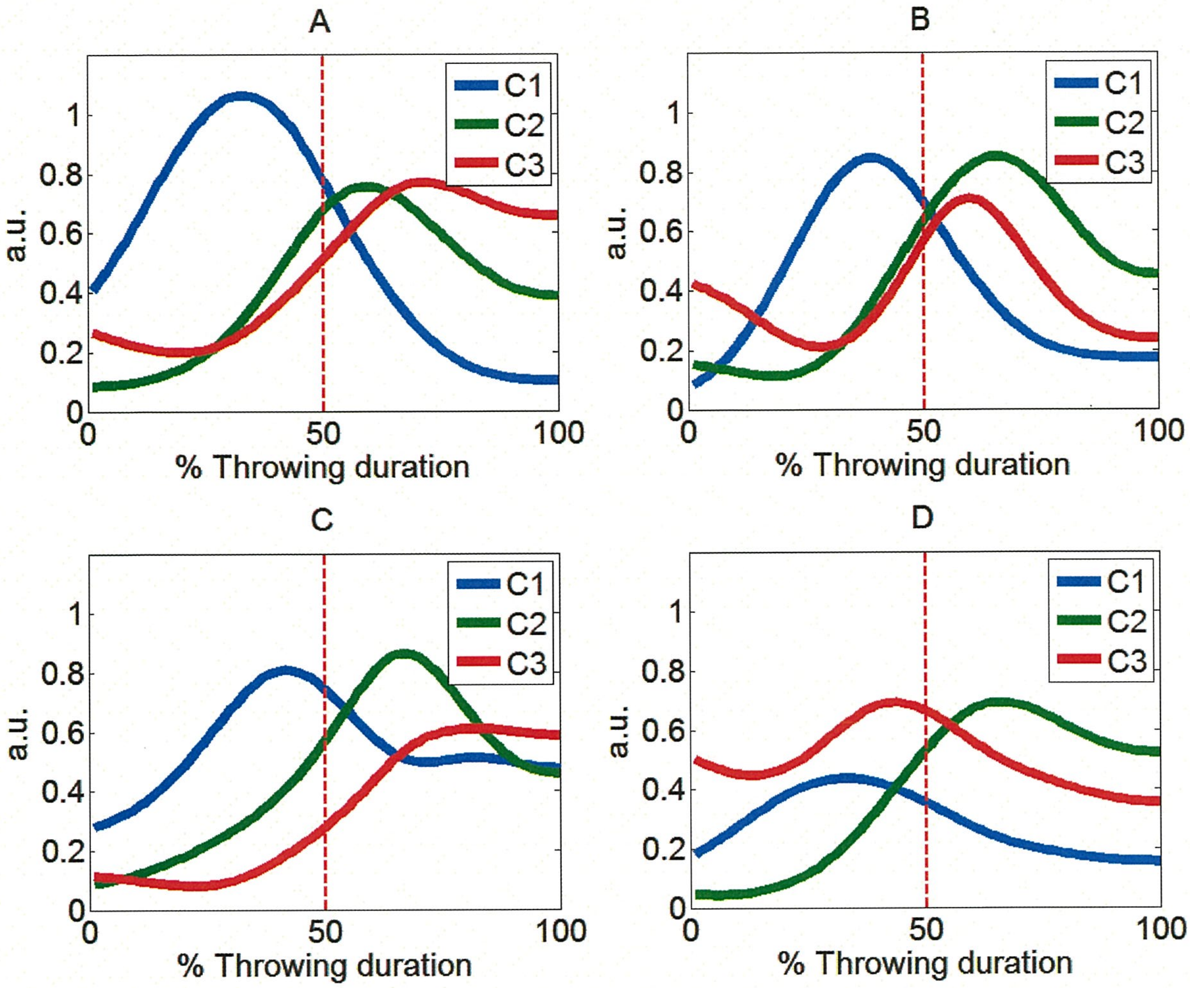

Figure 4-8. Activation coefficents of all participants.

Figure 4-8 illustrates the average of activation coefficients, or the time-series of synergies within an activation envelope, with total of 60 throws of all participants. The dashed red line is the time of release, 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.

4.2.3 Discussion

From the results, we can see that in dart throwing could be anatomically explained by a small set of muscle synergies in general across subjects. Generally, the patterns of activation coefficients (*C1*, *C2*, and *C3*) were similar between subjects because of the natural throw movement, i.e., elbow extension (driving the forearm) before the time of release, wrist flexion, and finger extension (to release a dart). However, the specific timing of the time-courses was different, i.e., in subjects A and C, *C3* activated immediately after the second synergy, while significant variability was observed in subjects B and D (see Figure 4-8). Similarly, in standing-up movement,

Under an anatomical viewpoint, *S1* with the most robust activation of *TB* drives the forearm forwards, or elbow extension. It is noticeable that subject D used more energy of the shoulder muscle (*AD*) to lift the upper arm during the acceleration phase. Meanwhile, *S2* and *S3* were subject-specific. In the second synergy (*S2*), in the case of subjects A and B, wrist muscles (*FR* and *FU*) were dominantly activated, which were corresponding to the wrist motion after the time of release to flex/extend the wrist joint. Meanwhile, dominant muscle activation of *EI* was observed in subject D at the time of release, which implies that the subject focused on the finger movement at the time of release. *S2* of subject C activated mainly the shoulder flexion, or lift the joint after the time of release. In the last synergy (S3), with dominant activations of *EI*, subject A focused on index extension, 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). An overwhelming activation of BR was found in the S3 of subject A and D, which could be explained by the antagonist activation to stop the movement since *BR* is synergistic with the *BB*.

In general, muscle synergies were suggested to be robust across subjects in previous studies while performing tasks with highly repeatable between trials such as walking [90], cycling [93-94], standing-up [92] and backward giant swings on the high bar [95]. For instance, the same three muscle synergies were identified in standing-up motion, and each synergy involved in one function, whatever under several conditions of chair heights and speeds [92]. In the movement, it is suggested that humans only control the activation coefficients to adapt the motion speed. Similarly, in complex motor skills, i.e., backward giant swings on the high bar [95], three muscle synergies were found (from six EMG-recorded muscles) that could explain approximately 90% of the variance accounted for 12 muscles on the upper-limb and trunk. These synergies were similar between performers, although there was variability in the third synergy.

Conversely, there were dramatically different between subjects in this experiment in terms of both temporal and spatial domains. Notably, two out of three muscle synergies in the current thesis were different between subjects. Because perhaps all subjects were beginners performed with free postures as opposed to experts, activities of the trunk and lower extremities were free, which might lead to the huge variability between subjects. Dart throwing is an intensive movement, which could result in some noise that might occur during a throw, which could affect the synergy extraction, especially in EMG recording systems using wire electrodes as in this experiment. Nevertheless, muscle synergies could explain the observed EMG data sufficiently ($r^2 = 0.91 \pm 0.02$) across four subjects, which could support the muscle synergy hypothesis [13], along with a wide range of motor behaviors [60].

Based on the two strategies classified by the timing sensitivity from the dart experts in Chapter 3, it would be interesting to clarify characteristic differences of the corresponding muscle synergies (spatial) and activation coefficient (temporal) in prospective studies. For instance, it would be expected that the activation level of the wrist (FU and FR) of experts with longer TWL in the second synergy, which activated near the time of release, is higher than those with shorter TWL because of the fast angular acceleration at the wrist joint.

4.3 Conclusion

In summary, this chapter provides the interpretation of muscle activities in dart throwing. First, the author has confirmed the reduced co-activation of antagonist muscle in skilled and intermediate level dart throwers, i.e., the activation level of *BB* was relatively lower than beginners. The finding supports the hypothesis that antagonist deactivation is considered as a motor skill achievement [20], which also has been confirmed in skilled tennis players and jumpers [59,84]. Since the reduction of the antagonist activation could be obtained in the early stage of training, it might be reasonable to reduce the effect of the negative activation by an isokinetic exercise for novices first, followed by a training course in terms of kinematic parameters.

Furthermore, a set of three muscle synergies could decompose the throwing movement, and the set could explain the observed data of 10 individual muscles along the throwing arm sufficiently, with the determination coefficient $r^2 = 0.91 \pm 0.02$. The result provides evidence to support the hypothesis of their existence to address the redundancy problem in the neuromuscular system.

Chapter 5. Conclusion

5.1 Significances

This thesis is a study in dart throwing gains insight into motor strategies of skills of dart throwers in terms of EMG and kinematics, by elucidating the expertise through both kinematics of human and dart movements and neuromuscular control.

In the kinematic analysis, this is the first study that has utilized the dart trajectory to analyze the timing sensitivity. We can measure the error on the dartboard directly by the capture system after a throw, which is more convenient instead of using other systems. Moreover, the prediction model based on the dart trajectory could estimate the final position more precisely than a previous model based on the finger trajectory [3]. Furthermore, the patterns of vertical error curves derived from the dart trajectory were more intuitive to analyze the timing sensitivity, with only one optimized timing point, instead of two [16, 17]. Two strategies of experts were confirmed, i.e., reducing timing error (Et) and increasing time-window length (TWL) for the successful release. A spatiotemporal relationship with the hand path elaborately explained the strategies of experts. Also, angular kinematics of human joints and kinematic profile of the dart at the time of release (location, speed, and angle) were confirmed to be correlated with the time-window length. These results imply that the skilled players have acquired the motor skills by elaborate coordination of human joints and dart in spatial or temporal controls. In future works, the findings in kinematics and timing sensitivity of this study should be carried out on skilled players in other similar sports require accuracy such as basketball and boccia to be clear expertise.

In terms of EMGs, the current thesis has investigated the co-activation of *Biceps brachii* and *Triceps brachii* between *beginner*, *intermediate,* and *expert* groups. The decreased activation of antagonist muscle (*BB*) was confirmed in the *intermediate* and *expert* groups, providing evidence for the hypothesis states that deactivation of antagonist muscle is considered as a motor skill [20]. Besides, the current thesis investigated muscle synergies in the dart throwing movement to support the muscle synergy hypothesis [13].

This analysis of several factors in the neuromuscular system in the sophisticated task of this study is informative for scientists in motor control and might provide a methodology to train novices. For example, in beginners who prefer to release a dart with the low arc, we can develop a training system that helps to improve the hand trajectories and wrist strength based on the feedback of corresponding error curves and neglect the error on the board in the early stage. Once the hand trajectory becomes similar to experts, the novice could practice with the darts.

5.2 Limitations and prospective studies

In this thesis, the author has clarified the motor strategies of highly skilled dart throwers through several kinematic parameters in spatial and temporal domains, as well as muscle activities through EMG signals. Some of the prospective works have been remaining.

Firstly, the sample size in this study (eight subjects) might not be sufficient to conclude the correlations of kinematic factors between the experts. It is necessary to investigate a more skilled dart thrower to confirm the strategies and underlying characteristics of experts. In the current study, two strategies were found from eight experts, but there is a high possibility that some experts performed the task with "average" values in both TWL and Et. If so, the "exact" strategies have been defined might not exist, it just complies a tradeoff between timing accuracy and timing sensitivity.

Secondly, since the target was unchanged throughout the experiment (bull's-eye) and the two best performers had different strategies, it was not clear to conclude which strategy was better. In fact, in a dart throwing game, the target is not only the inner or outer bull's-eyes, where the scores are 50 or 25 points, respectively. For instance, in a "501 up" game, where the score is reduced specific points corresponding to the value on the dartboard after a throw, and the first player who reduces to exactly zero wins the game. Therefore, the ability to throws any targets accurately on the board has to be acquired. In other words, in the experiment design, the targets should be changed dynamically onto double or triple rings, which multiply the score by a factor 2 or 3, respectively, to "reduce" the point from 501 quickly. Thus, it is appealing to examine how experts with different strategies change kinematic parameters and timing sensitivity to adapt dynamic targets on the dartboard.

Finally, the number of subjects in muscle synergy analysis was not sufficient (only four), and all were beginners, who performed dart throwing with "unexpected" movement patterns such as lift the shoulder too high or moving the lower body to supply force for the throw. Therefore, muscle synergies of skilled experts (with an appropriate data size, e.g. 20 throwers) would be conducted since the experts performed the task consistently and effectively (e.g. know how to reduce the degrees of freedom by minimization of elbow or shoulder movements during the acceleration phase), which could give insights into the human neuromuscular system.

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